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Miehe, Frederick William, Jr.; Bird, Robert A.

Cambridge, Massachusetts; Massachusetts Institute of Technology

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An Investigation of the Application of the Laws of Similitude to Electric Flashtubes

by

F.W.Miehe Jr. and R.A.Bird
under the supervision of
Dr. H.E.Edgerton

Submitted ----- 20 May, 1949

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SUMMARY

Object:

This thesis endeavors to express the behavior of electrical flashtubes in an analytical manner and to evaluate the relative importance of operation parameters.

Procedure:

The techniques of procedure were all directed toward a correlated accumulation of significant data. The primary variables studied were voltage, capacitance, flashtube length, and flashtube diameter. Figure V through X indicate the method of procuring and coordinating data. Figures XI through XVII show the means by which data was analyzed.

Results:

Within the present practical area of flashtube operation, the following empirical expressions were derived:

$$V = \frac{65 L}{\sqrt{C L}} \eta + 135 D^2 \eta \quad (4)$$

$$V = \frac{65 L}{\sqrt{C L}} \eta + \frac{13.3}{D^{1/2}} \left[\eta - \frac{8.3}{D^{2/3}} \right] \quad (5)$$

$$\eta = \frac{8.3}{D^{2/3} [1 - 10.12 D^{5/2}]} \quad (6)$$



... of qualitative ... is new ...
... of ... of ...
... of ...

Conclusions:

The primary conclusion is that the derived expressions for the ... for approximate ... operation ... error that ... exceeds five percent. ... therefore serve as a ... means ... of this ... operation can be defined ... predicted with ... of this work.

Recommendations:

A more fundamental expression for the ... operation appears to be desirable and possible. This could ... be written through ... the efficiency ... curves of ... V to K. The ... of ... indicates ...

INTRODUCTION

The electrical flashtube is a device which converts electrical energy into light energy. This conversion is not complete, but a large portion of the electrical energy is converted into heat, sound, and mechanical force. In fact, an electrical input of 120 watt sec. and a light output of 4800 lumen sec. would not be uncommon. The ratio, lumens per watt, is called the efficiency, and an efficiency of 40 is a good operating value for most applications. The duration of the flash is of the order of several hundred micro-seconds.

In order to obtain these characteristics, a capacitor placed in parallel with the flashtube is used as the electrical storage element. It is charged to a certain value of voltage and subsequently discharged through the flashtube. This process can be repeated indefinitely within practical limits. A flashtube is simply a glass or quartz tube filled with gas and incorporating two electrodes, one at each extremity. The gas can be one of several; argon, hydrogen, Xenon, and krypton are typical, although Xenon finds the most general application. Flashtubes are constructed in many shapes. Several straight and curved tubes have been developed, although it has been found that such shapes as the helix or spiral give a more concentrated light source. The lengths of tubes, whatever their ultimate forms, are great compared with

their diameters.

As might be surmised applications of flashtubes are diverse. The various factors which determine application are tube efficiency, spectral distribution of light output, flash duration, size and type of power supply, ruggedness of unit, ability to repeat flashes at given intervals of time, and number of flashes obtainable during tube life. In a given application it is impossible to obtain the best of all factors. Many factors may be entirely unimportant in comparison with one salient characteristic which may be essential to a given application.

Specific examples of the application of flashtubes are aerial night photography, stroboscopic photography, landing approach lights for airfields and aircraft carriers, and electric circuit triggering with photocells as detectors.

Proper design of flashtubes then is important, and it should be as precise as possible. At the present time, flashtubes are designed through knowledge of past performance of flashtubes of known characteristics. Quantitative relationships do not at present exist among the various physical parameters such as tube length, tube diameter, voltage, capacitance, type of gas, gas pressure, efficiency, spectral distribution, and flash duration. Design is conducted solely on an empirical basis.

This thesis attempts to accomplish two objectives.

One is to find, through experimental data, some fundamental relationships which exist among specified parameters. The second objective is to write an empirical expression which can be used to predict tube behavior under specified conditions. The number of variables are strictly limited in order to place the thesis within practical bounds. The limitations will be clearly stated in subsequent sections. Specifically, the variable parameters are tube length, inside diameter, voltage, capacitance, and efficiency. The flashtubes used are straight. A total of three sets were constructed of glass, all of which contain Xenon at a pressure of 15 centimeters of mercury. The dimensions of the tubes are as indicated in Table I. A photograph of set no. 3.4 is included as Figure I, comparing tubes within this set and indicating their form and size relative to a standard commercial flashtube, FT-214, which is manufactured by the General Electric Company. Table II shows the basic symbols used and their definitions.



TABLE I

Tube Dimensions

Set Number	Inside Diameter (inches)	Length between electrodes (inches)	
		Nominal	Actual
3.4	0.133 (3.4mm.)	2	2.07
		3	3.09
		4	4.11
		5	5.04
		6	6.06
		7	7.11
4.6	0.189 (4.8mm.)	3	3.07
		4	4.06
		5	5.09
		6	6.20
		7	7.12
5.5	0.217 (5.5mm.)	3	3.01
		4	4.06
		5	5.12
		6	6.18
		7	7.07

NOTE: Glass-blowers tolerance is 0.125 inches for length.

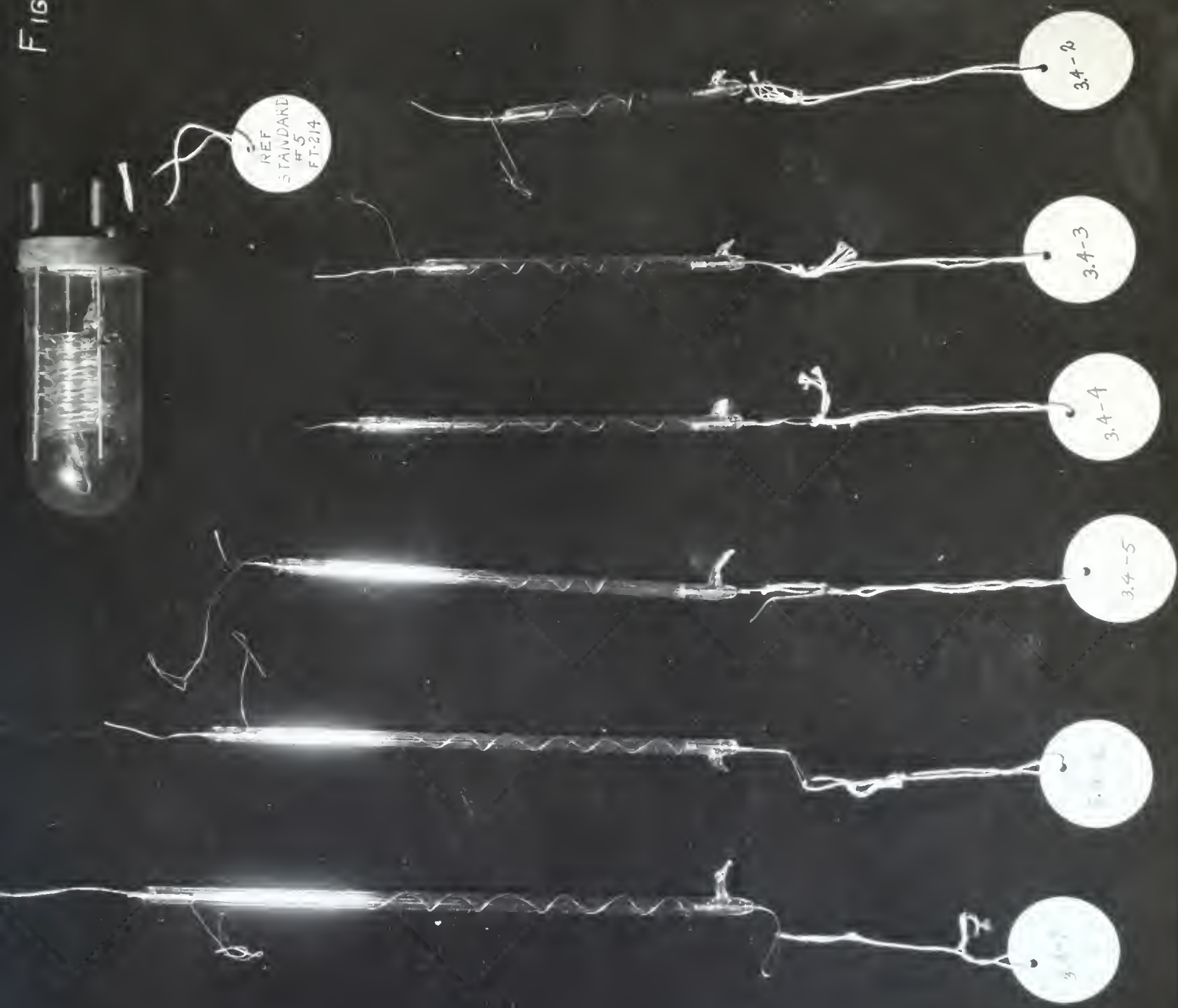


TABLE II

Table of Symbols

- η - Tube efficiency expressed in lumens per watt.
- D - Tube inside diameter expressed in inches.
- L - Tube length between electrodes expressed in inches.
- C - Capacitance in micro-farads.
- V - Voltage in volts.
- P - Gas pressure expressed in centimeters of mercury.

FIGURE I



PROCEDURE

Method Used in obtaining Data:

In a discussion of methods of obtaining data it is necessary to state the limits within which the experimental work is conducted. The quantities to be evaluated were light output and electrical power input. Measurement of light flux presented the greatest problem. A General Radio Integrating Lightmeter, Type 1501-A, Serial #115 was used to measure light flux, the final result being light flux in lumen seconds. The lightmeter and its use are discussed completely in Appendix A1.

The detecting device in the lightmeter is a photocell the surface of which is most sensitive to wave lengths in the blue region of the spectrum. The light output of the flashtube occurred toward the blue region of the visible spectrum. There was good correlation between the output and the detecting device in this regard. However, it is possible that the light pulse tended to shift along the frequency spectrum as the energy level changed. It is also possible that the photocell became saturated before the peak intensity of the light pulse was reached. This possibility is illustrated by Figure II.

This means that a portion of the light output would not be detected. Photographs of the light pulse were made, and it was found that the peak intensity fell within the

range of the photocell. This then was not a serious limitation.

The light meter was not capable of measuring total light output from the flashtube. This could have been accomplished only by the use of an integrating sphere. The lightmeter was actually used to measure horizontal candle power. If the flashtube were considered a point source with uniform light output, the conversion factor from horizontal candle power to lumen seconds would be 4π . The distance between light source and detecting device in this work was kept great enough so that the flashtube approximated a point source. The distribution of light output was not uniform because of end effects at the electrodes of the flashtube. For this reason a conversion factor of 10 was used instead of 4π . This is a reasonable assumption; moreover, relative effects were desired more than absolute quantities. Since the factor was applied uniformly, the results of the work are not jeopardized.

It was impossible to obtain absolute values of light output. Again the relative effects were of prime importance. The vital problem was to be able to repeat readings from a known standard, the standard being General Electric's FT-214.

The light meter was calibrated to the standard lamp which is displayed in Figure I. All data therefore can be repeated if the standard is assumed. It must be remembered

then that all subsequent development is based on this standard and not on absolute quantities.

The final limitation of possible significance is the residual voltage that remains on the capacitor after it has discharged through the flashtube. It may amount to as much as 100 to 200 volts. However, it was impossible to measure this voltage because of the characteristics of the voltmeter and because of the recharging of the capacitor immediately after its discharge. The residual voltage was necessarily neglected during the experimental work. It appears as a limitation for all of the data. However, it is felt that the effect of residual voltage is relatively unimportant.

In order to restrict the field of experimentation within practical limits, Xenon was used exclusively as the tube gas. Furthermore, the pressure of the gas was held at 15 centimeters of Mercury in all flashtubes. Tubes were all constructed of glass tubing, the inside diameter of which was kept as uniform as possible in manufacture and measured to the nearest tenth of a millimeter. Details of tube manufacture are included in Appendix A3.

In order to obtain the essential quantities for this thesis it was necessary to measure accurately light output, voltage and capacitance. Techniques of measurement were developed so that all errors in measurement were reduced to

Computations for these values are found in Appendix B.

These ideas did not lead directly to the solution as indicated in this thesis. However, the intermediate work is considered important enough to be included as part of this investigation. Consequently, Appendix A4 contains this preliminary work and an attempt is made to show its possible value.

Data was accumulated in the form of an efficiency curve, η versus V , for each tube with its capacitance as listed in Table III. A family of efficiency curves for each tube set was plotted for analysis. These curves are illustrated in Figures V to X. It should be emphasized at this point that the efficiency curves within a family are related to each other by the equation

$$LC = \text{Constant} \quad (1)$$

The portions of the efficiency curves illustrated are considered to be the useful portions for practical work. They are bounded on the low voltage side by a region where the voltage is not sufficient to cause the capacitor to discharge through the flashtube. The high voltage boundary is established at a voltage beyond which the tube is likely to be damaged.

From these families of efficiency curves, another family of curves was plotted which was a representation of Length versus Voltage for constant efficiency within the

using the following equation: $\eta = \frac{m}{\sqrt{C L}}$ where m is the slope of the linear plot of $\log \eta$ versus $\log C$. The values of η were obtained for each tube set. These values of η were plotted as a function of efficiency with $\sqrt{C}$ as a parameter. The resulting graph is shown in figure 1. The relationship obtained appeared as a linear plot with a line passing through the origin. The following equation was written which included the constant K as a constant. The equation is of the form:

$$\eta = K \sqrt{C} \quad (1)$$

where m is the slope of the linear plot of $\log \eta$ versus $\log C$. The values of η were obtained for each tube set. These values of η were plotted as a function of efficiency with $\sqrt{C}$ as a parameter. The resulting graph is shown in figure 1. The relationship obtained appeared as a linear plot with a line passing through the origin. The following equation was written which included the constant K as a constant. The equation is of the form:

$$m = \frac{K}{\sqrt{C L}} \eta \quad (3)$$

where m is the slope of the linear plot of $\log \eta$ versus $\log C$. The values of η were obtained for each tube set. These values of η were plotted as a function of efficiency with $\sqrt{C}$ as a parameter. The resulting graph is shown in figure 1. The relationship obtained appeared as a linear plot with a line passing through the origin. The following equation was written which included the constant K as a constant. The equation is of the form:

equation (3) and solving for k_2 . This calculation is made in Appendix B. The same procedure was used in attempting to determine the intercept b . Experimental values of b were plotted as a function of efficiency with $\sqrt{CI}$ as the parameter. The results are illustrated in Figure XVII. The form of the curves rendered analytical analysis impracticable. An approximate form for b was devised, and it also is illustrated in Figure XVII. The derivation of this form for b may be found in Appendix B.

In order to study results, various values for $\sqrt{CI}$ were used. The variable here, of course, is Capacitance which served to vary the energy level at which a tube set was operated. These values of Capacitance are listed in Table III.

TABLE III
Table of Capacitance

Tube Number	Length (inches)	Capacitance (micro-farads)	
		Calculated	Used
3.4 - 2	2.07	51.76	50.74
		103.56	103.56
3.4 - 3	3.09	34.7	34.82
		69.4	69.84
3.4 - 4	4.11	26.07	26.73
		52.15	52.92
3.4 - 5	5.04	21.28	21.32
		42.55	42.46
3.4 - 6	6.06	17.7	18.44
		35.4	35.84
3.4 - 7	7.11	14.8	14.84
		29.6	29.56
4.8 - 3	3.07	139.1	138.79
4.8 - 4	4.06	105.1	105.16
4.8 - 5	5.09	83.9	84.8
4.8 - 6	6.20	68.85	69.84
4.8 - 7	7.12	60.0	60.56
5.5 - 3	3.01	186.3	180.32
5.5 - 4	4.06	52.15	52.92
		69.05	69.84
		137.1	137.77
5.5 - 5	5.12	109.5	108.32
5.5 - 6	6.18	55.4	55.84
		45.35	45.37
		90.7	87.92

TABLE III (CONT'D)

Table of Capacitance

Tube Number	Length (inches)	Capacitance (micro-farads)	
		Calculated	Used
6.5 - 7	7.07	29.6	29.56
		39.65	40.07
		78.3	79.54

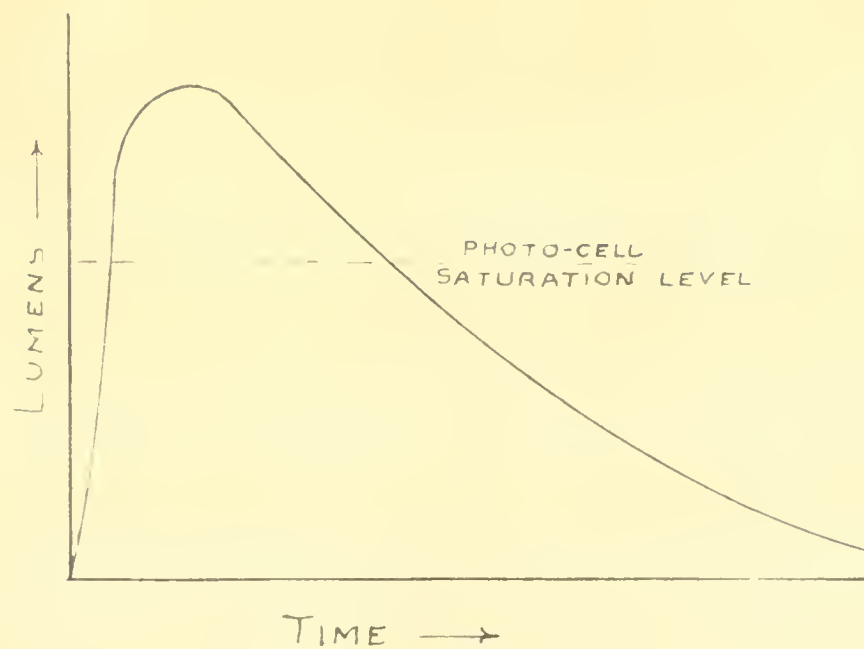


FIG. 2 LIGHTMETER PHOTOCELL SATURATION.

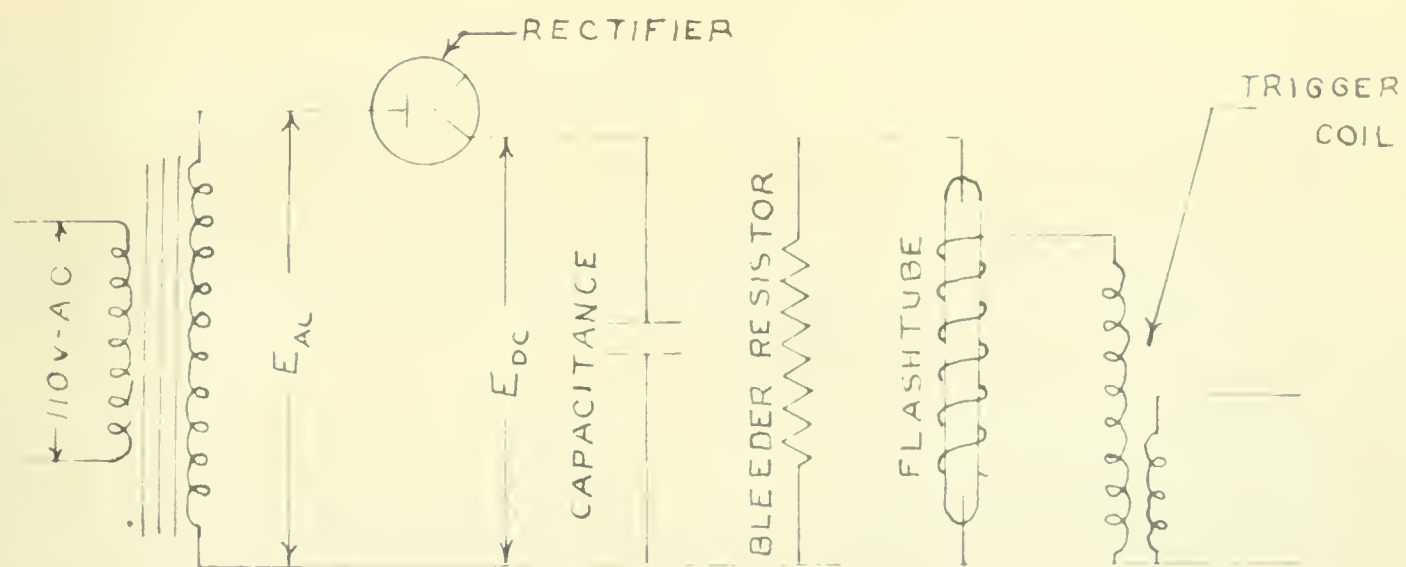
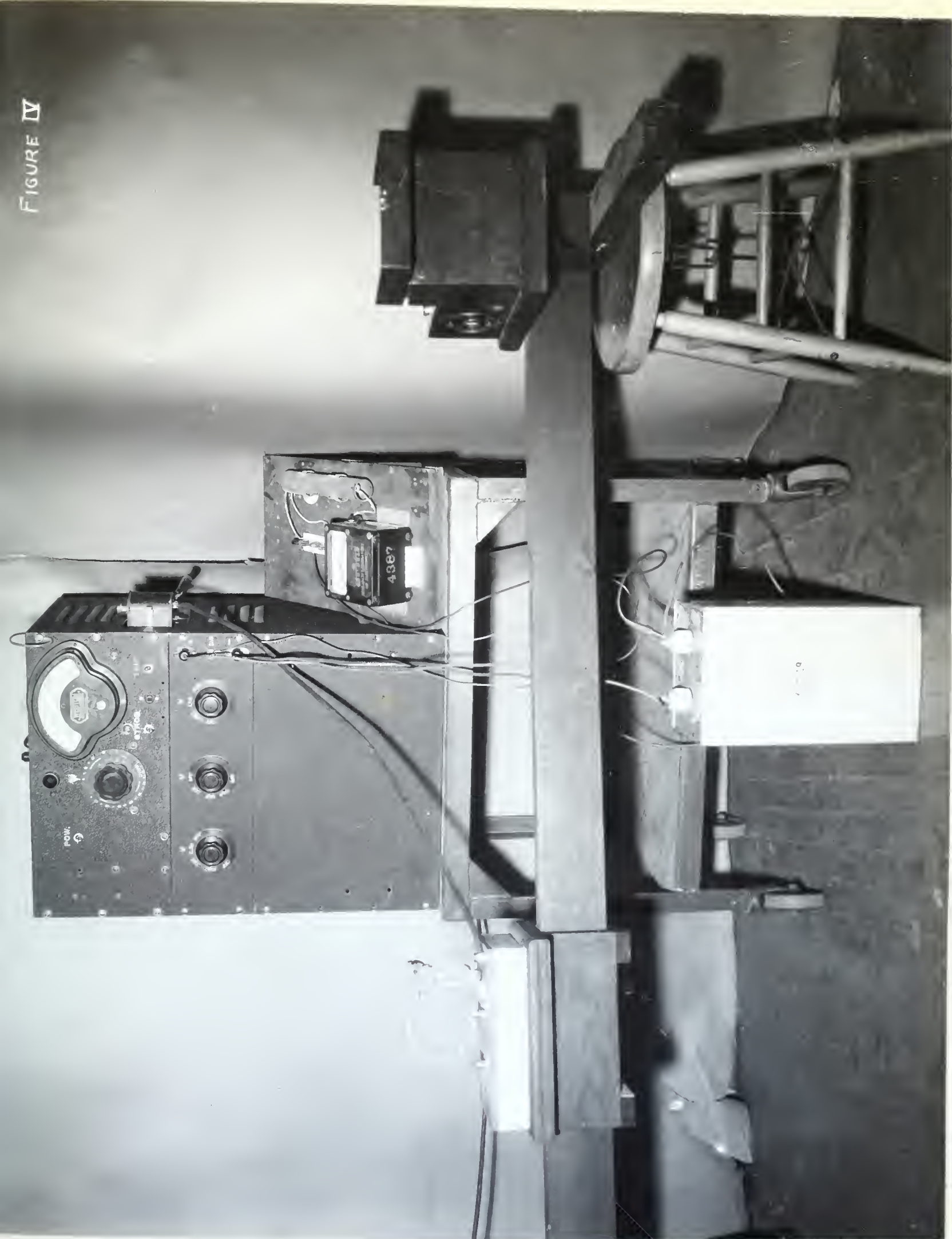
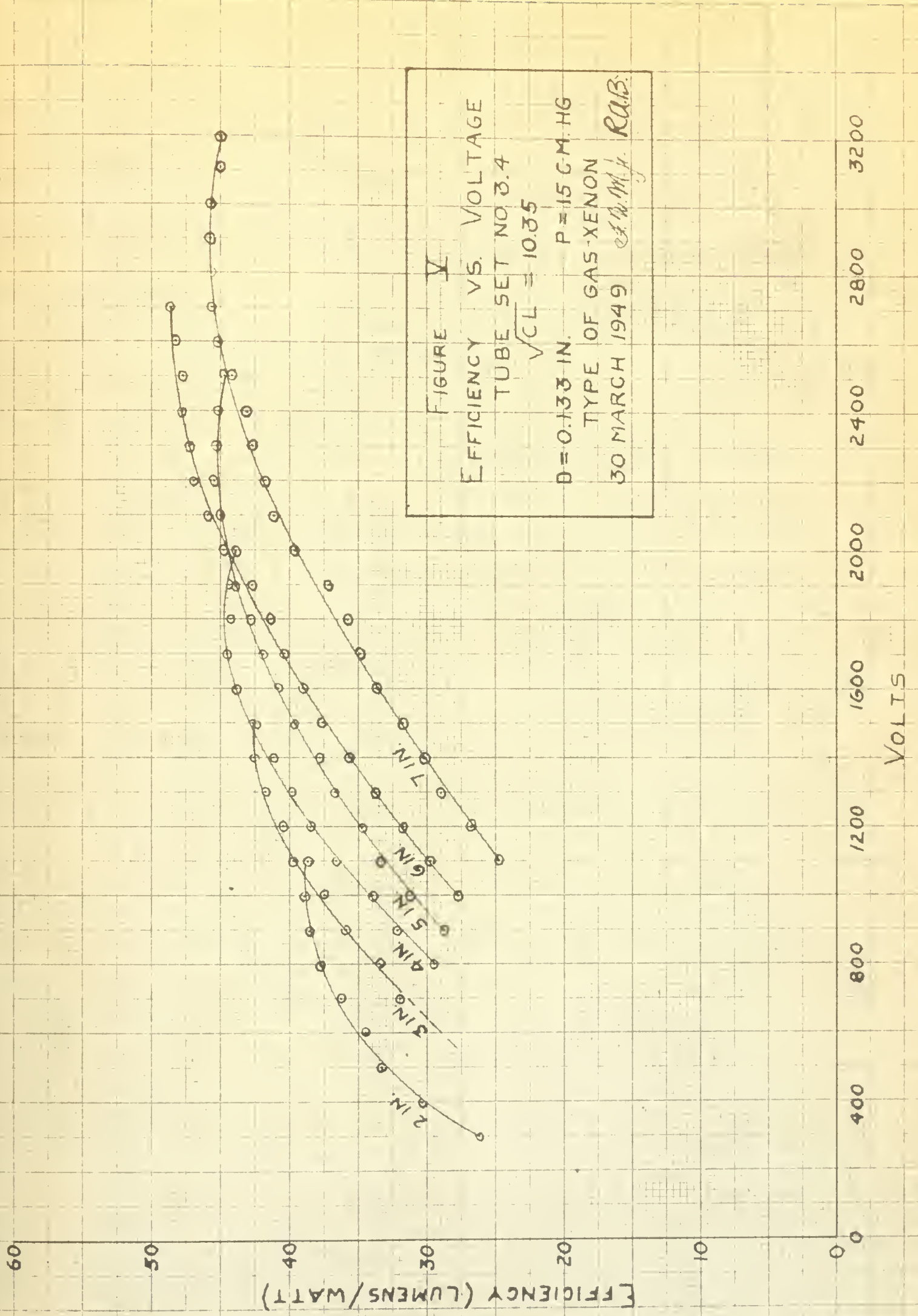
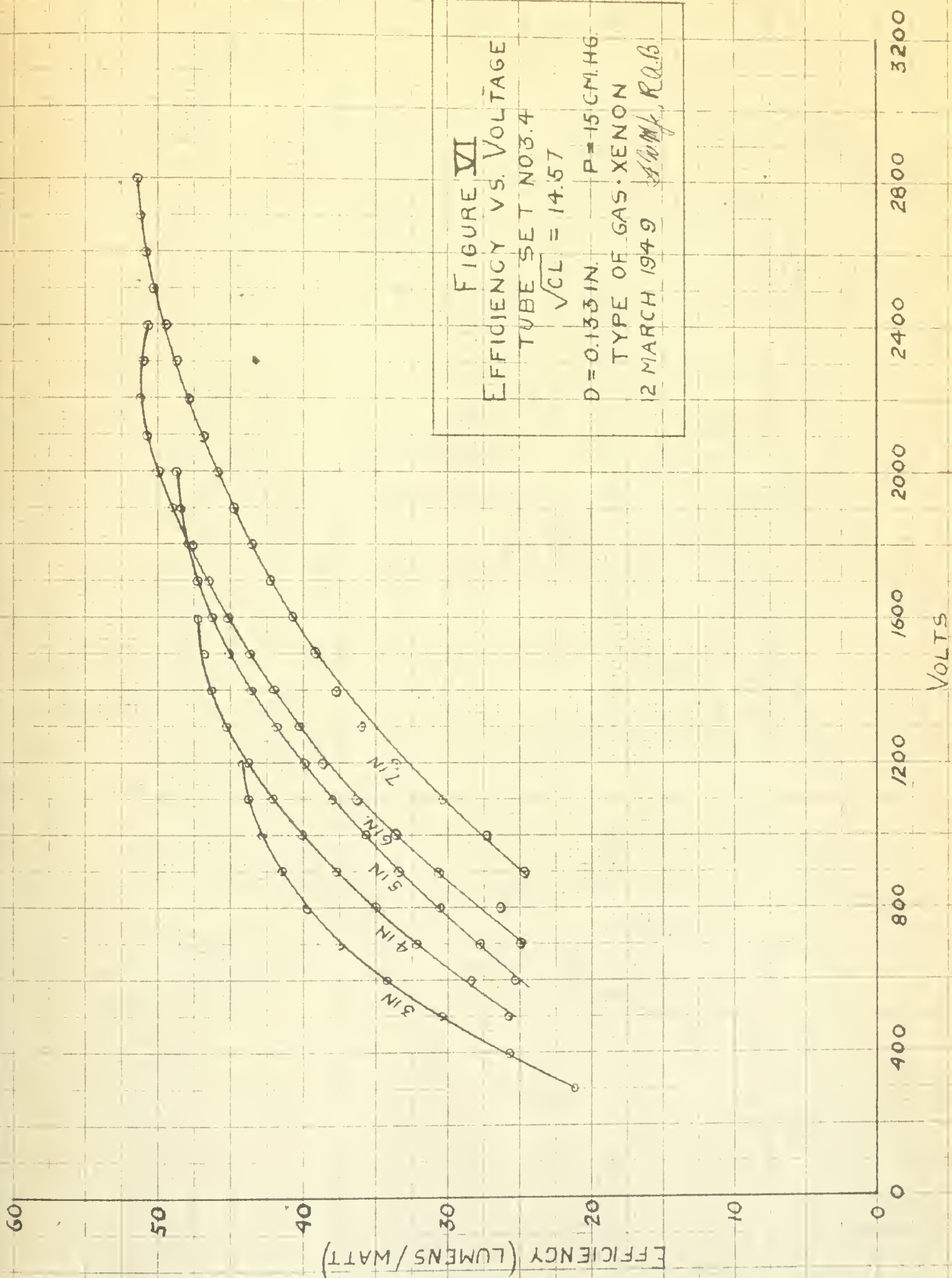


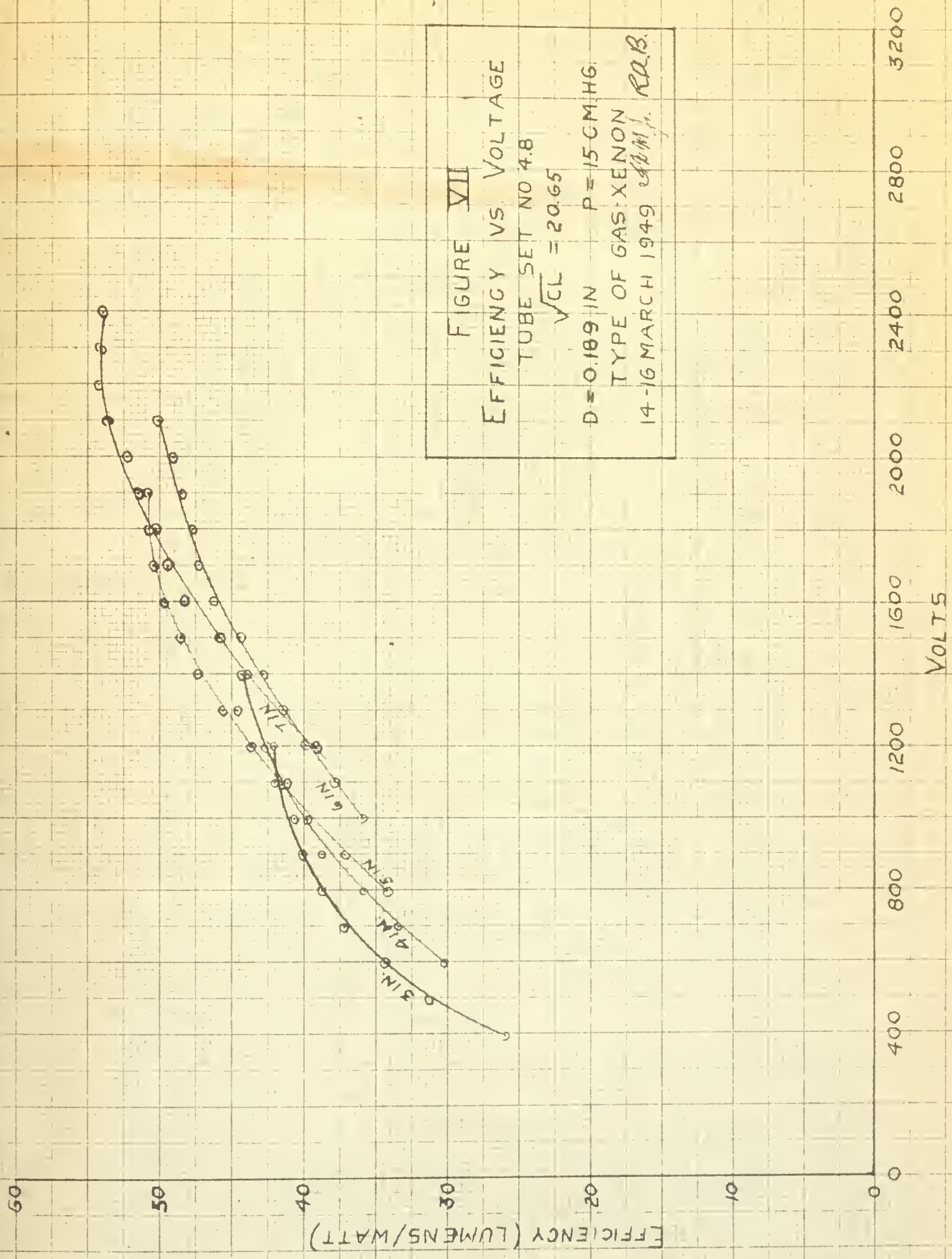
FIG. 3. SCHEMATIC DIAGRAM FOR FLASHTUBE OPERATION.

FIGURE IV









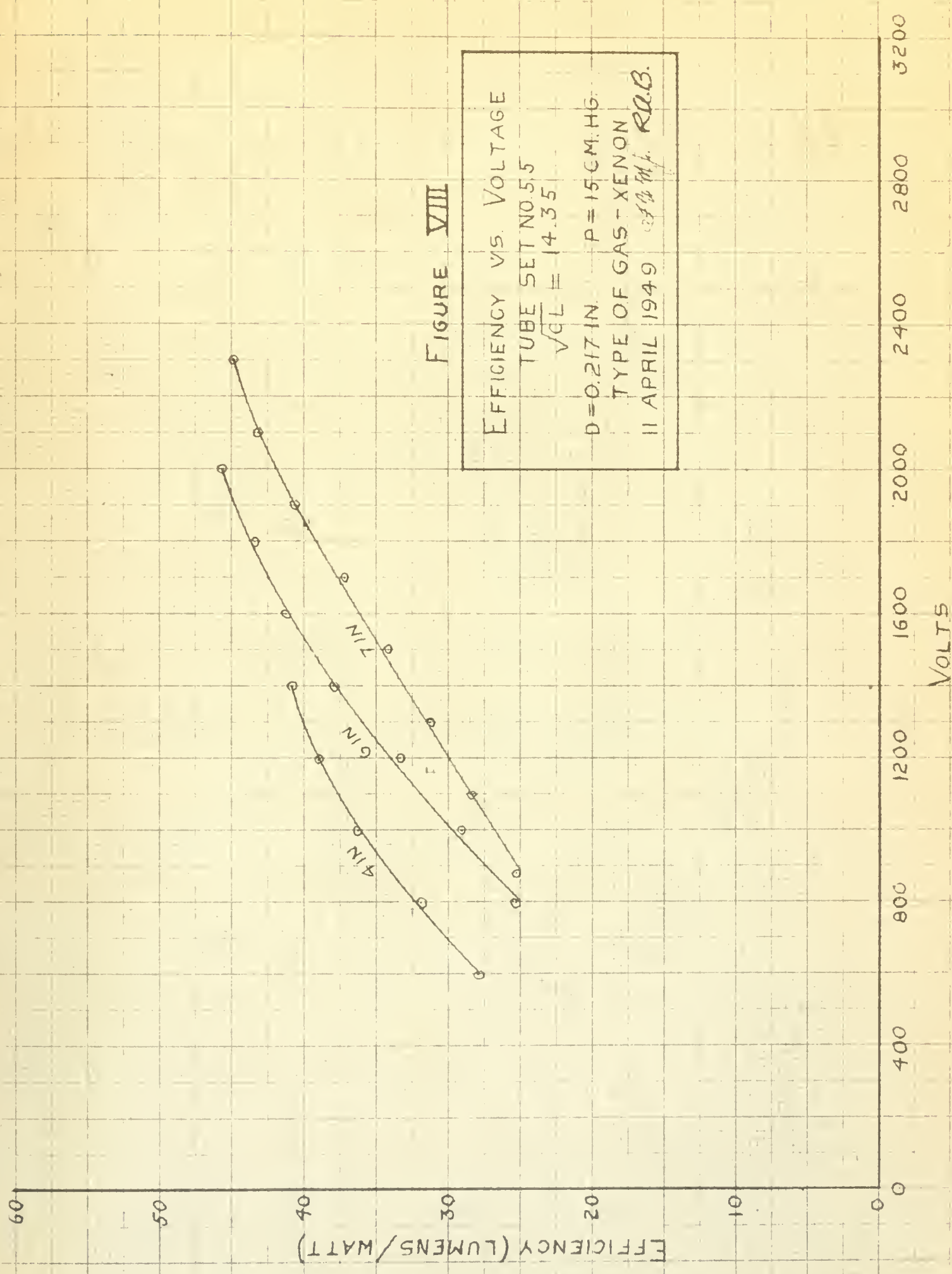


FIGURE VIII

EFFICIENCY VS. VOLTAGE
TUBE SET NO. 5.5
 $\sqrt{GL} = 14.35$
D = 0.217 IN. P = 15 CM. HG.
TYPE OF GAS - XENON
11 APRIL 1949 *W. M. R.A.B.*

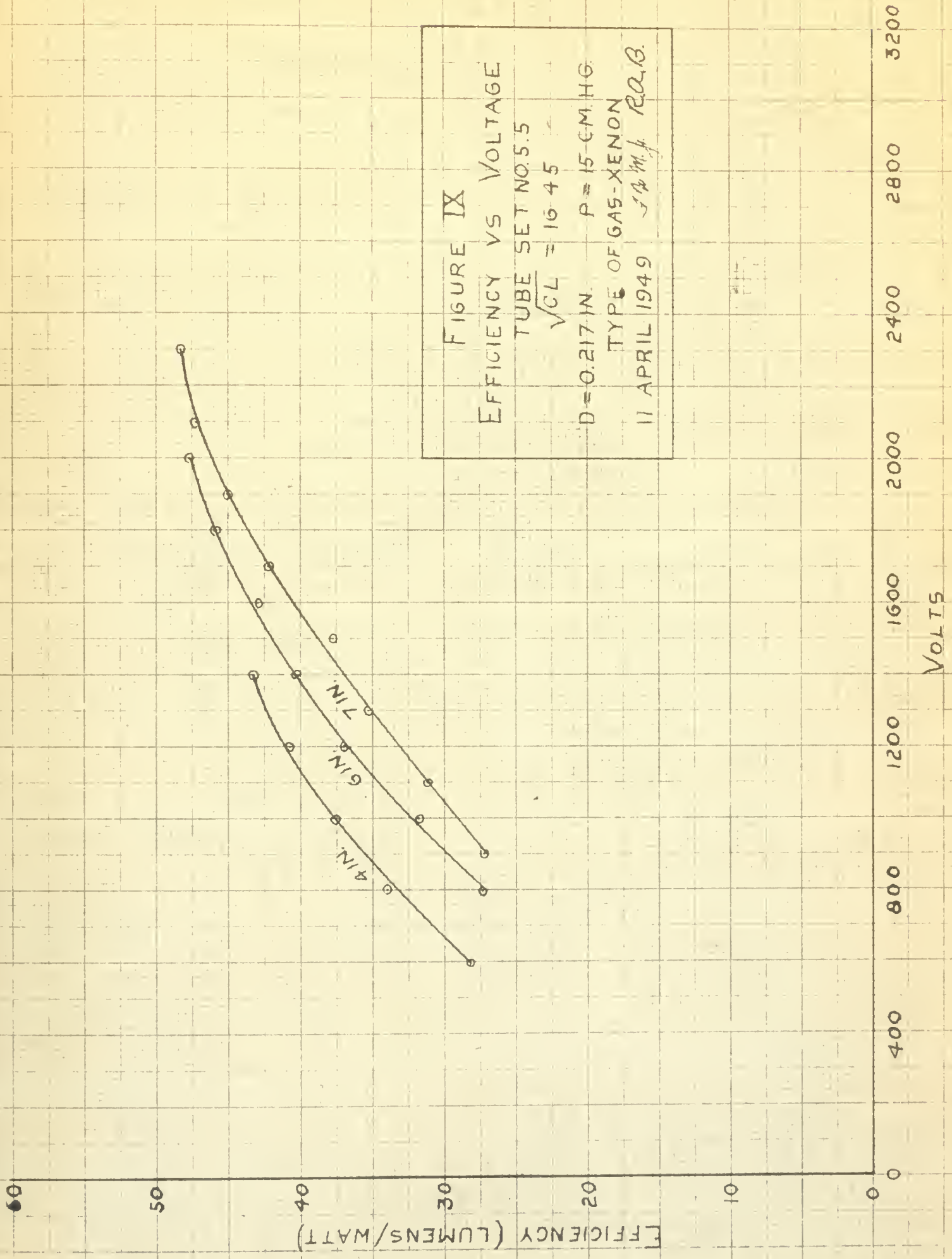


FIGURE IX
 EFFICIENCY VS VOLTAGE
 TUBE SET NO. 5.5
 $\sqrt{CL} = 16.45$
 $D = 0.217$ IN. $P = 15$ CM. HG.
 TYPE OF GAS - XENON
 11 APRIL 1949 *J. M. R. R. B.*

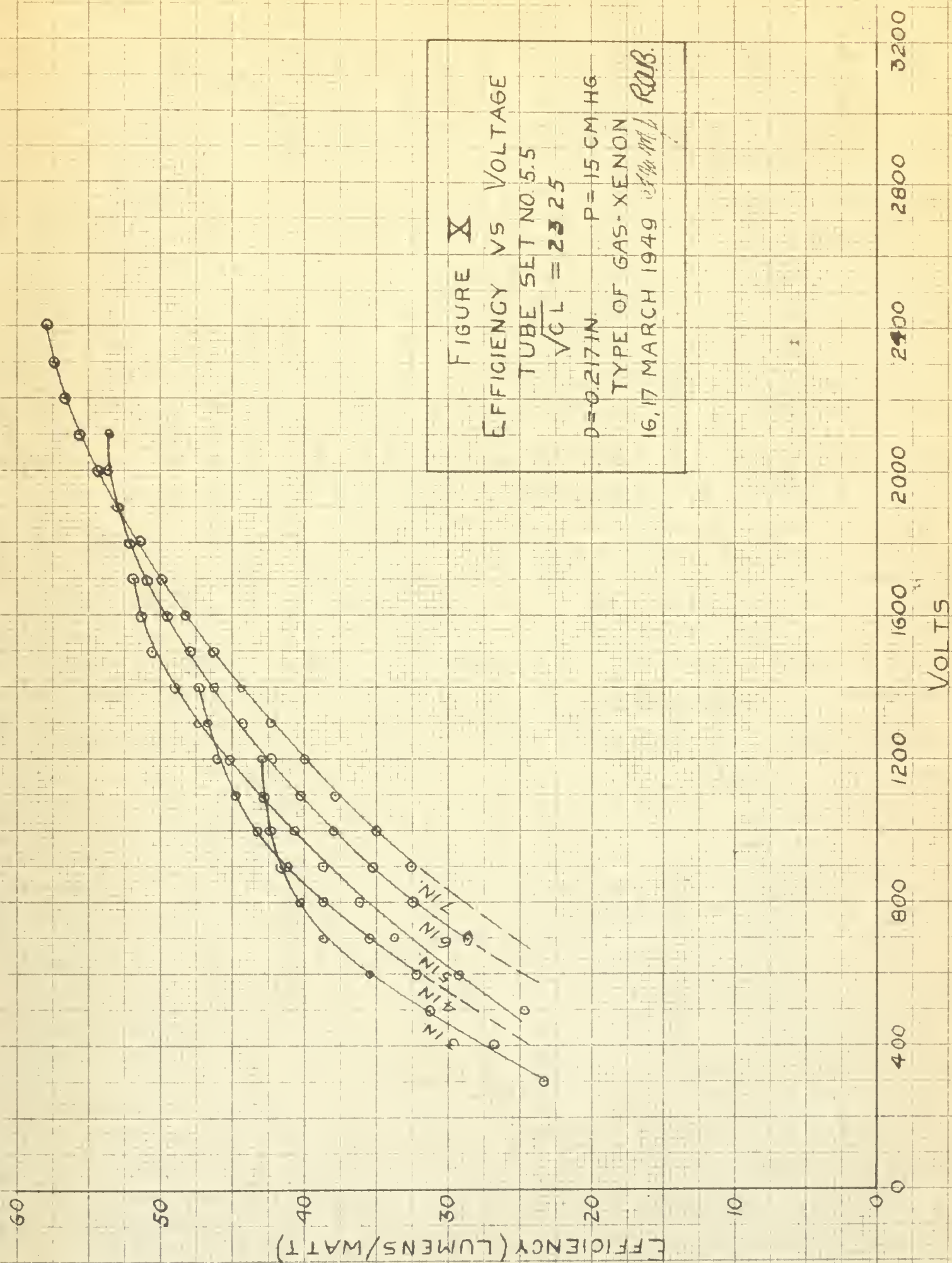


FIGURE X
 EFFICIENCY VS VOLTAGE
 TUBE SET NO. 5.5
 $\sqrt{CL} = 23.25$
 $D = 0.217$ IN. $P = 15$ CM HG
 TYPE OF GAS - XENON
 16, 17 MARCH 1949 *Frank Rab.*

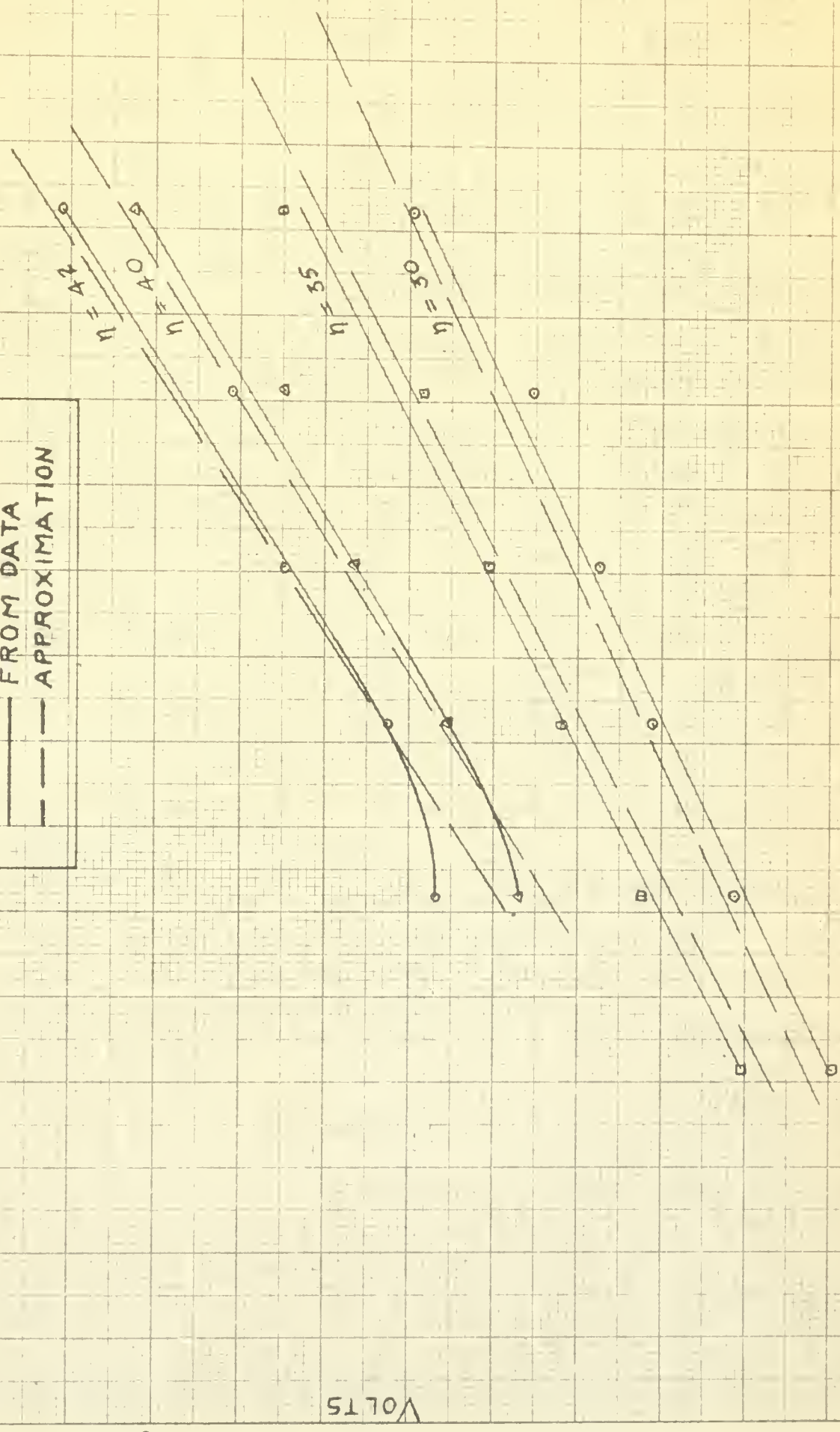
FIGURE XI

VOLTAGE VS. LENGTH
TUBE SET NO 3.4
 $\sqrt{LG} = 10.35$

D = 0.133 IN. P = 15 CM. HG.

TYPE OF GAS - XENON

— FROM DATA
--- APPROXIMATION



VOLTS

LENGTH (INCHES)

FIGURE XII

VOLTAGE VS. LENGTH

TUBE SET NO. 3.4

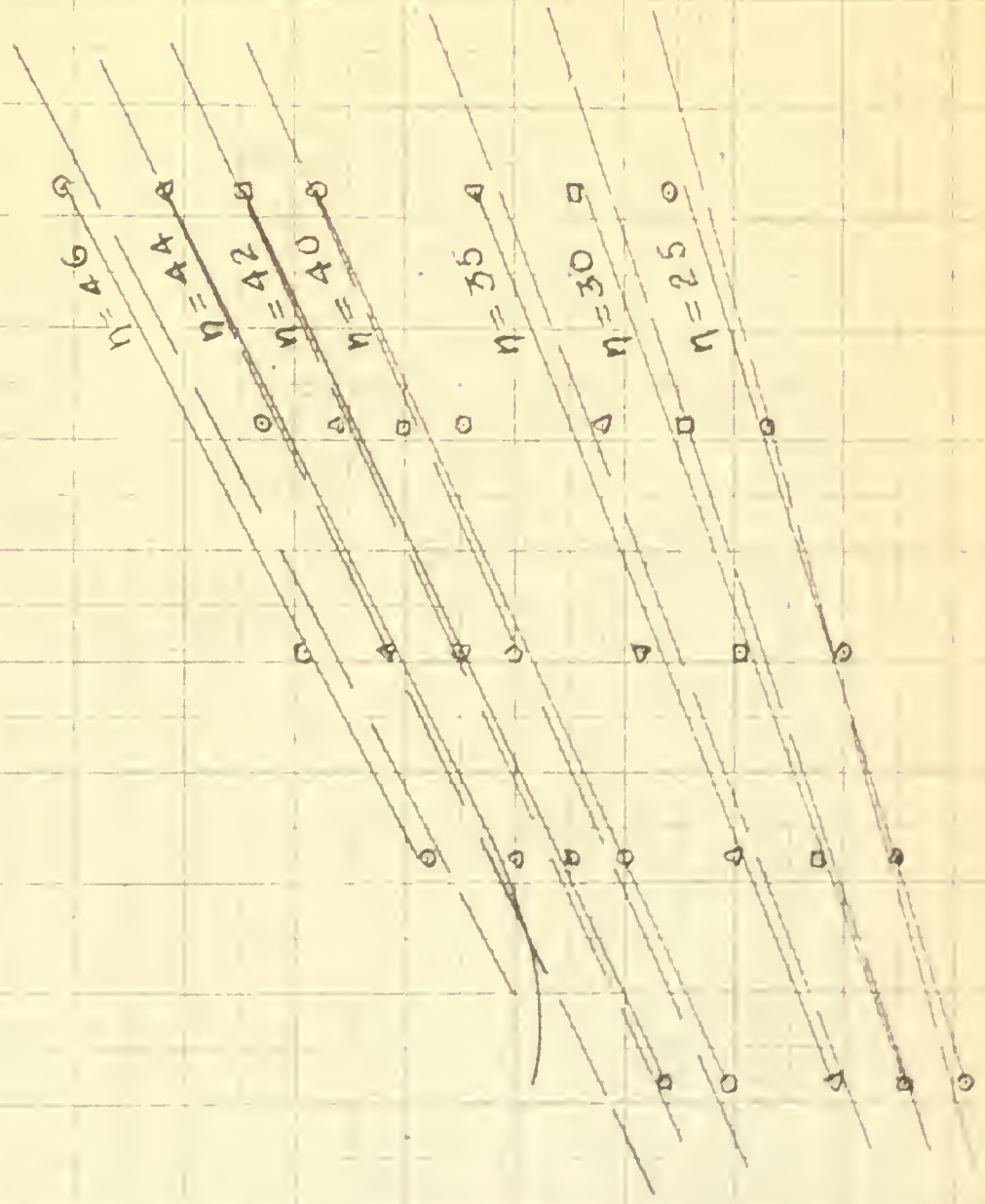
$\sqrt{LC} = 14.57$

$D = 0.133$ IN $P = 15$ CM. HG.

TYPE OF GAS - XENON

— FROM DATA

--- APPROXIMATION



LENGTH (INCHES)

0 500 1000 1500 2000 2500

FIGURE XIII

VOLTAGE VS. LENGTH
TUBE SET NO. 5.5

$$\sqrt{GL} = 14.35$$

D = 0.217 IN. P = 15 CM. HG.

TYPE OF GAS - XENON

— FROM DATA

--- APPROXIMATION

VOLTS

LENGTH (INCHES)

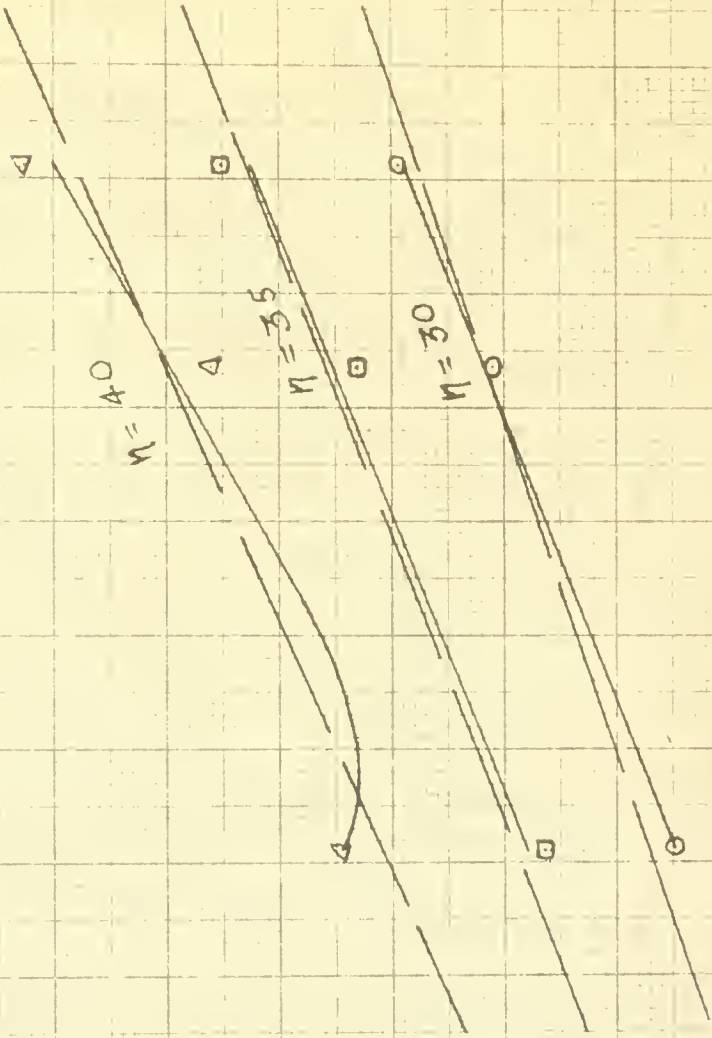


FIGURE XIV

VOLTAGE VS. LENGTH

TUBE SET NO. 5.5

$\sqrt{L_G} = 16.45$

$D = 0.217$ IN. $P = 15$ CM. HG.

TYPE OF GAS - XENON

— FROM DATA

--- APPROXIMATION

VOLTS

LENGTH (INCHES)

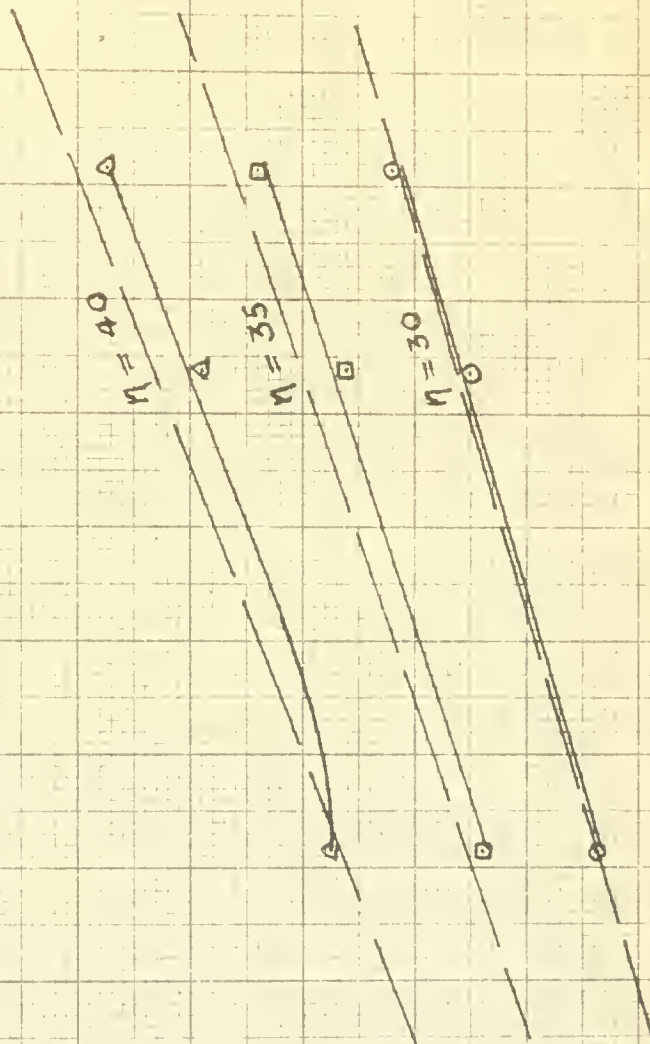


FIGURE XV

VOLTAGE VS. LENGTH
TUBE SET NO. 5.5

$\sqrt{CL} = 23.25$

D = 0.217 IN. P = 15 CM. HG.

TYPE OF GAS - XENON

— FROM DATA

--- APPROXIMATION

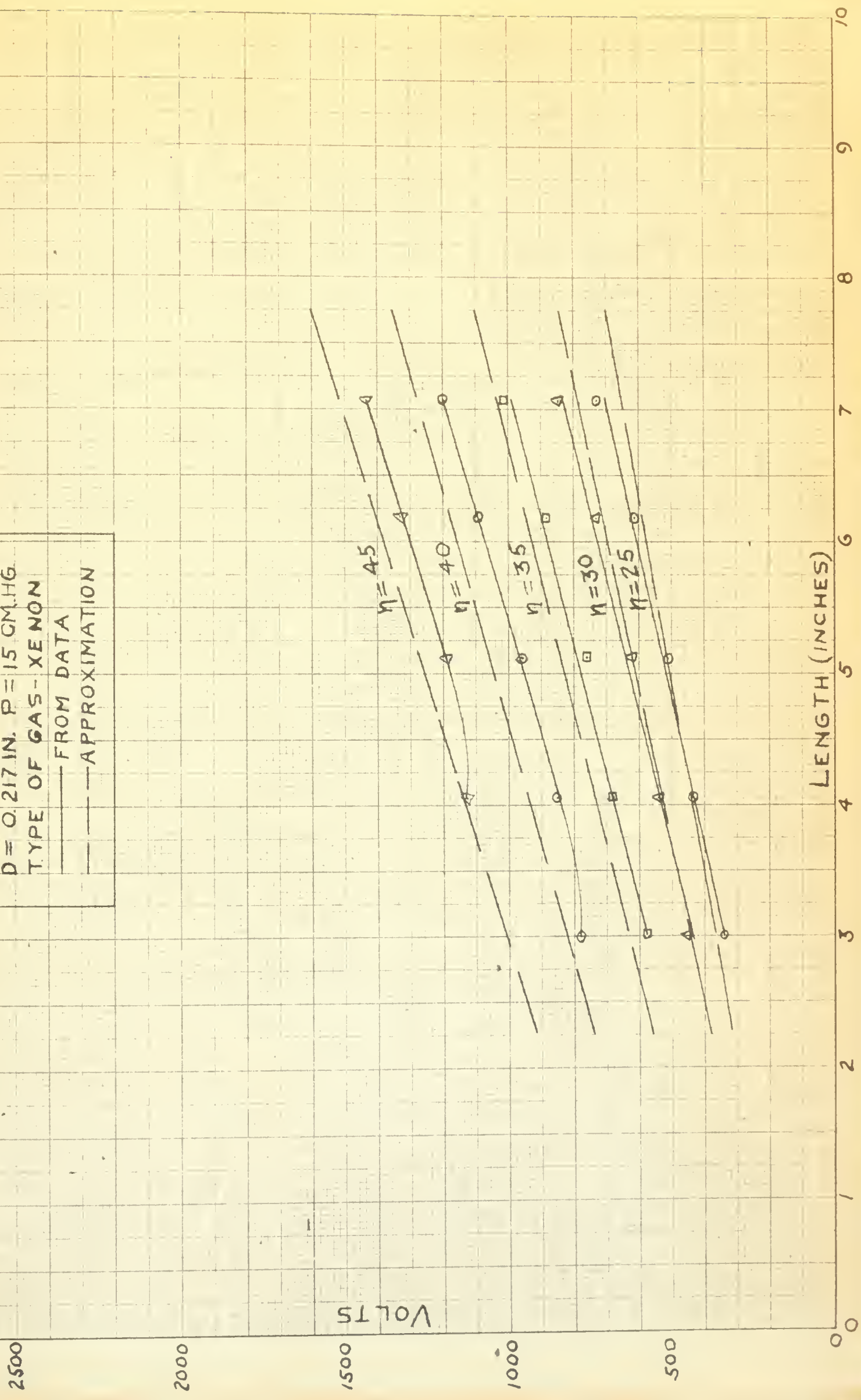


FIGURE XVI
SLOPE VS. EFFICIENCY
TUBE SETS NO. 3.4 155

SLOPE "m" (VOLTS/INCH)

EFFICIENCY (LUMENS/WATT)

$$m = \frac{65}{\sqrt{CL}} \eta$$

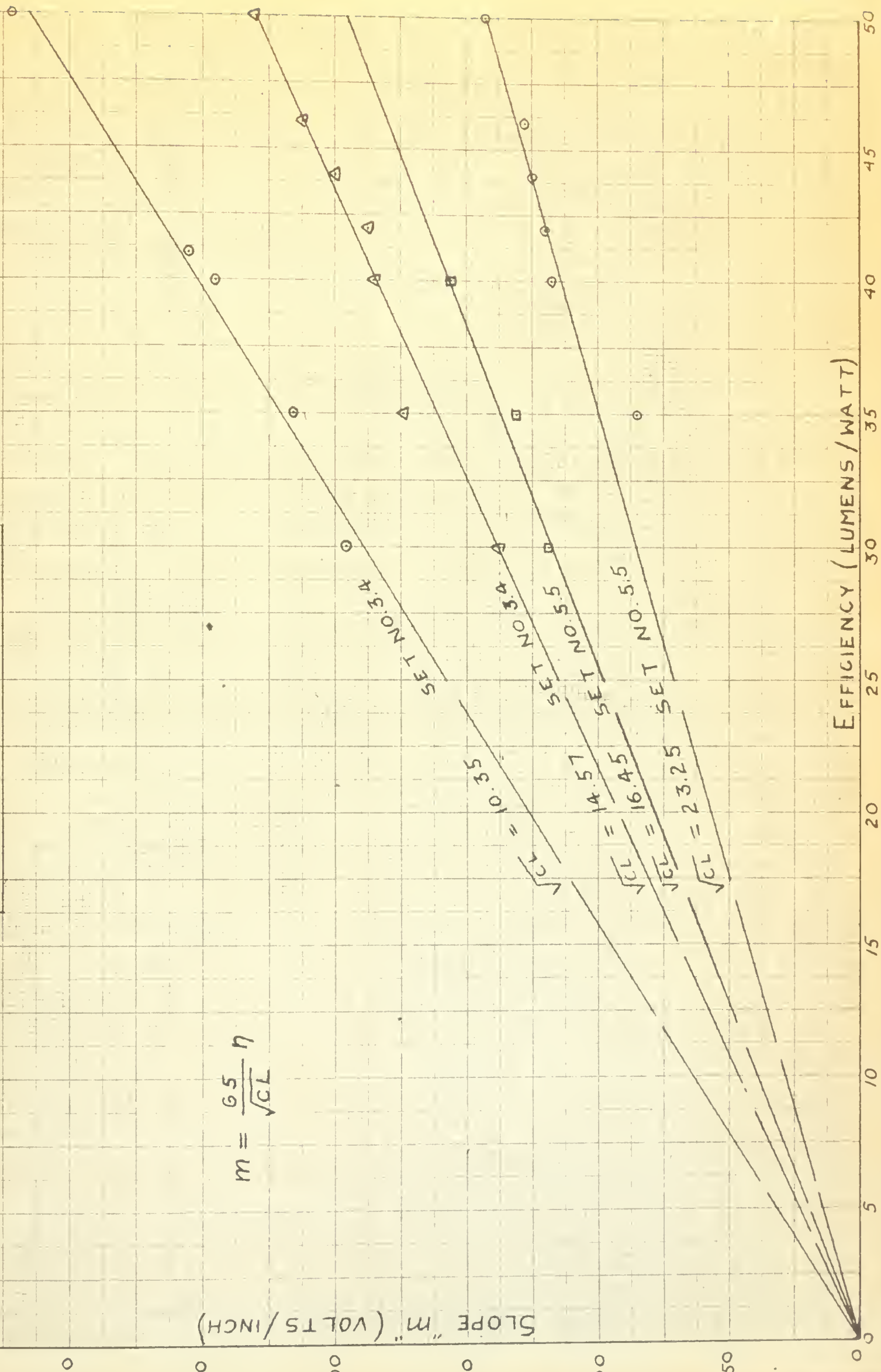
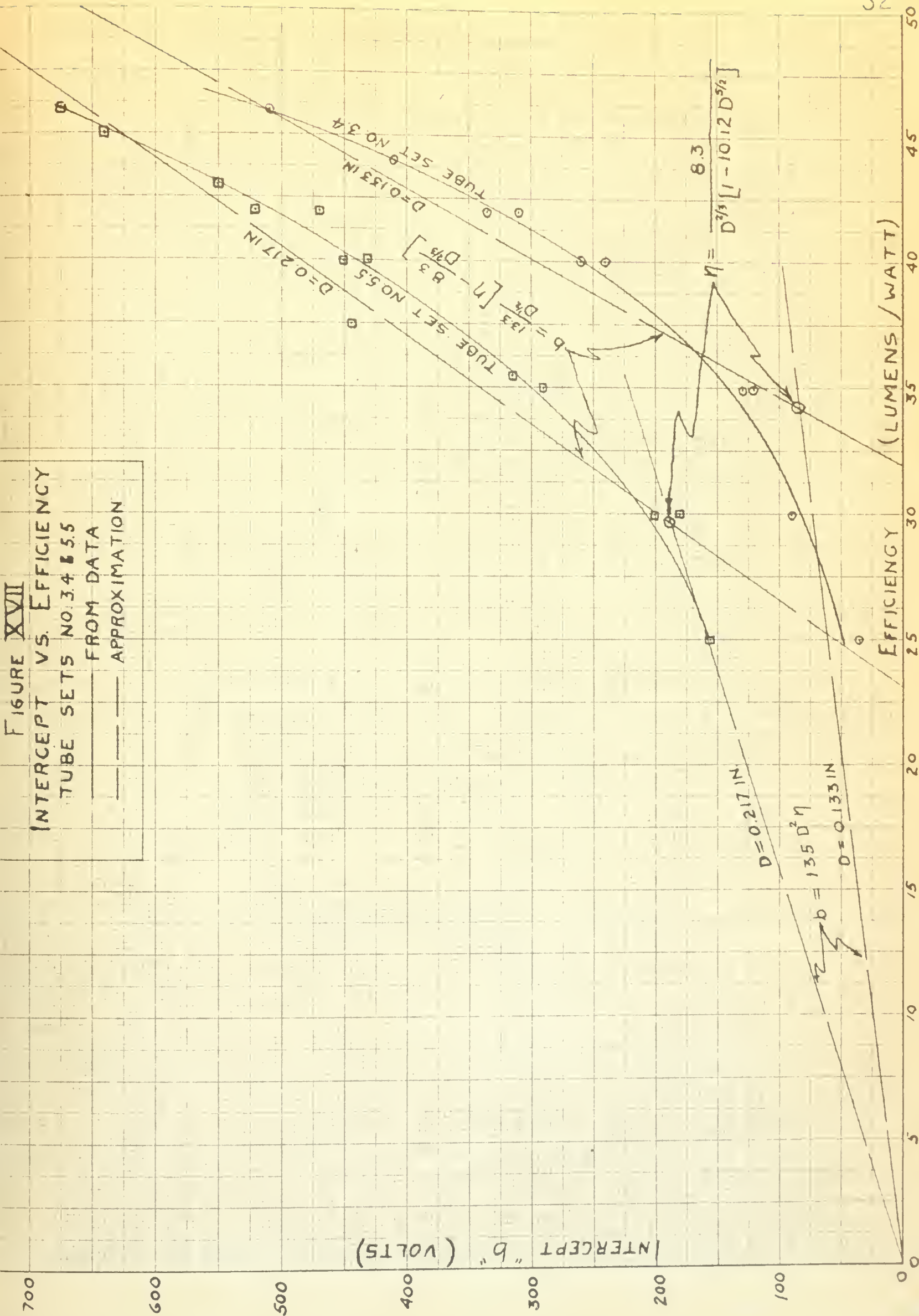


FIGURE XVII

INTERCEPT VS. EFFICIENCY

TUBE SETS NO. 34 & 55

— FROM DATA
 --- APPROXIMATION



RESULTS

The results obtained in this work are of a dual nature. Analytical expressions have been obtained which define flashtube behavior within the established limits of the thesis. The expressions appear to show a maximum error from experimental results of about five percent.

The second form of results is in the nature of observed phenomena. These phenomena will be stated and an explanation will be attempted where possible in the Discussion of Results.

The empirical formulae derived from experimental data are;

$$V = \frac{65L}{\sqrt{CL}} \eta + 135 D^2 \eta \quad (4)$$

$$V = \frac{65L}{\sqrt{CL}} \eta + \frac{13.3}{D^{1/2}} \left[\eta - \frac{8.3}{D^{2/3}} \right] \quad (5)$$

$$\eta = \frac{8.3}{D^{2/3} [1 - 10.12 D^{1/2}]} \quad (6)$$

Equations (4) and (5) are extensions of equation (2) with m and b defined. It was impossible to approximate b by a single expression. Consequently, two straight line

approximations were used. The transition point between the two regions is indicated by equation (6) from the simultaneous solution of the intercept expressions in equations (4) and (5).

The efficiency versus voltage curves, for a single tube with capacitance as a parameter, possessed characteristic shapes. A single curve is roughly parabolic in shape. It rises to a maximum efficiency and then descends as voltage is increased. The ascending and descending portions appear to be roughly symmetrical in the vicinity of maximum efficiency about a constant voltage line through the maximum efficiency point; or where,

$$\frac{d\eta}{dV} = 0 \quad (7)$$

As capacitance is increased, the maximum efficiency increases but not in a linear manner with capacitance. The maximum efficiency occurs at lower voltages as capacitance is increased and the slopes, $d\eta/dV$ and $-d\eta/dV$, increase in the directions indicated. It is this regularity in behavior that encourages analysis. For a pictorial representation of a family of efficiency curves for a single tube see reference (1) in Appendix C.

The most important aspect of flashtube behavior is the amount of energy that can be converted to light in the flashtube without damage to the tube upon repetitive flashing.

Damage is manifested by an extremely minute check-work of cracks in the glass tube. This is called "crazing". It was observed that crazing first begins as a circular crack whose plane is perpendicular to the long axis of the tube. These rings begin near the tip of the electrode, and as crazing increases, the cracks spread toward the center of the tube. As crazing becomes more severe, the circular pattern is lost. At no time was crazing observed to occur behind the electrode regardless of the severity of crazing. Furthermore, crazing did not affect the operation of the tube in any manner whatsoever until it had progressed to such a degree that the glass was no longer transparent. At this point the efficiency dropped, presumably because of the filtering effect of the crazed glass. Severely crazed tubes were re-flashed after several weeks of inactivity, and it was discovered that efficiency was not reduced. This indicates that the cracks were not great enough to allow contamination from outside air. A preponderance of experimental evidence indicated that crazing does not occur until after the peak of the efficiency curve is reached. Table IV lists the various quantities involved at the point where crazing was first observed. This table is included to give the reader an idea of relative magnitudes of voltage, capacitance, efficiency, and energy input.*



An attempt was made to observe effects of gas contamination. It was impossible to evaluate this effect except in a few indirect cases. It was found to be roughly three sources of contamination. The most severe case of contamination occurs when a plate actually leaks and the gas is admitted. The gas will not operate. A less severe case occurs when the gas is contaminated and the plate is difficult to operate even in cases of the tube to tube. The least severe case of contamination occurs in all glass tubes, and it is merely a result of liberation of trapped impurities from the glass walls and electrodes. This, of course, is a function of the excellence of the clean-up process. The cause of this general classification can be made in that contamination can be observed in all cases by exciting the gas in the tube. In the case of complete contamination it is impossible to obtain a continuous glow between electrodes.

* Ideas concerning crazing are based also upon data obtained in preparation for the thesis. The glass tubes investigated were of the same construction as those investigated in the thesis proper.

the gas is excited. In the other two cases contamination is observed by a characteristic greenish glow associated with oxygen. The difference between the two cases is only a matter of the amount of greenish glow. The significant facts associated with contamination are revealed in tube operation. Operation is impossible when contamination is complete. If the glow is continuous between electrodes, but predominantly green, the tube can be operated. In spite of firing difficulty there appears to be no differences in operation between a tube with this degree of contamination and a tube with little or no contamination. A tube exhibiting contamination associated with the third class fires well at low voltage and operates consistently at all energy levels. The only significance that contamination has for this case is that it is detectable.

An unusual circumstance was noted which may possess some significance for an experimenter more astute than the authors. Immediately after pumping and curing a flash-tube, the gas was excited. The characteristic bluish glow of xenon permeated the entire tube with a somewhat more intense glow in the line between electrodes. After the tube was flashed approximately fifty times, the gas was again excited. It was found that the glow was all concentrated in the line between electrodes, and never again during the tube life did the all pervasive glow appear.

A final observation which may be associated with gas contamination was made while taking readings of light output. When repetitive flashes were made with identical capacitance and voltage on one tube, the first flash would very often indicate an increased light output over the series of four or five supposedly identical flashes. This occurred most often when the tube had not been in operation for long, and it had not been heated by repeated flashing.

TABLE IV

Tabulation of Parameters at Point of Crazing

Tube Number	Voltage Volts	Energy Input (Watt seconds)	*Location on Efficiency Curve in Relation to Peak
3.4 - 4	1600	67.7	on peak
3.4 - 5	2500	67.2	after
3.4 - 7	2800	116.0	after
4.8 - 3	1200	99.8	after
4.8 - 4	1550	101.9	after
4.8 - 5	1900	118.9	on peak
5.5 - 3	1150	119.1	after
5.5 - 4	1300	116.3	before
5.5 - 6	2350	242.5	after

* "After" or "before" must be defined as slightly after or slightly before, that is, at a value of efficiency very little less than the maximum value, and at a higher or lower value of voltage.

DIVISION OF RESULTS

Sufficient discussion has been given to techniques of assembling data in other parts of the thesis so that a discussion of results could very well begin with a realization that measurement errors have been minimized. Data obtained for the efficiency curves of Figures V through X was reasonably consistent. Data could be repeated, and poor data could be detected by various means. The authors, therefore, are confident of the reliability of data with certain exceptions which will presently be discussed.

The selection of a constant CL, capacitance in microfarads and length in inches, for relating data among tubes of a given diameter was a happy coincidence. It is definitely an outgrowth of the original concepts involving proportionality between Voltage and length and proportionality between input energy and tube volume. These concepts are covered in more detail in Appendix A4. The selection of the capacitance range was somewhat arbitrary, although the selection was tempered by previous experience with similar tubes. The value of $C = 103.56$ micro-farads for tube 3.4-2 was used as a basis for computing all other capacitances.

An inspection of the efficiency curves of Figures V through X shows a regularity of performance among flash-tubes of one diameter, but varying length, where CL is

maintained constant. This regularity lends itself readily to analysis. It has been stated that a family of efficiency curves for one tube shows specific characteristics where capacitance is varied. Where tube length is also varied in a set of tubes of one diameter, and capacitance is varied inversely with length, the shorter tubes with higher capacitance reach their maxima at lower voltages. Their ascending and descending slopes are greater. This behavior conforms to that of a single tube efficiency family. One important difference may be noticed when the single tube efficiency family is extended to include several tubes of varying length. As capacitance is increased and length consequently reduced, the maximum efficiency point is lowered. For a single tube efficiency family an increase in capacitance brings with it an increase in the maximum efficiency. From the curves of the 3.4 set displayed in Figures V and VI it can be concluded that as length increases, the maximum attainable efficiency increases. The maximum efficiency must occur at a higher voltage, however, in the case of the longer tubes. It appears from these two Figures that the increase in value of the maximum efficiency with increase of length tends to decrease. Figure VI represents identically the conditions of Figure V except that the capacitance range has been doubled. The maxima have all been increased over those

of Figure V. Moreover, the increase in maxima with increase in length is more pronounced at this higher capacitance range. In this inspection of the 3.4 set the data for the six inch tube must generally be used with discretion. It occupies a relative position which indicates that its capacitance was too high. It is definitely known that the capacitance was correct for this tube. The result cannot be explained, but a possible variation in processing the tube may have caused its unusual behavior.

The implications to be drawn from the efficiency curves of Figures V to X are many and varied. It must be remembered that they were constructed for the specific purpose of facilitating quantitative analysis. Sufficient information is included with the curves to enable the reader to make a study suitable to his needs. The study presented for the 3.4 set is offered as a guide to thought. This same study can be applied to set 5.5 in Figures VIII to X. All of the discussion that was conducted for the 3.4 set applies with equal force to the 5.5 set whose diameter is greater than that of the 3.4 set. In fact, trends that were presented in the 3.4 set are more pronounced for this increased diameter. In passing, it must be noted that the capacitance range for the 5.5 set of Figure X was computed on a proportionality basis involving the squares of the inside diameters, the base being tube 3.4-2 at 103.56 microfarads. The capacitance range of Figure IX is one-half

that of Figure 3. The capacitance range of Figure VIII is identical to that of Figure VI. Figures VIII and IX were plotted for a specific purpose which will appear later in the discussion.

Before leaving the subject of efficiency curves it is necessary to explain the results obtained in the 4.8 set. The efficiency curves for this set are plotted in Figure VII. While these curves indicate the general trends previously discussed, the data did not indicate the regularity which was so helpful in tube sets 3.4 and 5.5. Consequently, it was decided to concentrate effort on analysis of sets 3.4 and 5.5. The effect of diameter was more pronounced for these sets. After performing the analysis, tube set 4.8 was investigated in light of the derived formula. Random efficiency points were used for each tube of the 4.8 set. The efficiency and voltage was tabulated for these points. Using equations (4), (5), and (6), observed efficiency, tube length, diameter, and capacitance a calculated value of voltage was obtained for each observed efficiency. An efficiency was then obtained from Figure VII using these calculated values of voltage. These efficiencies were finally compared with experimental efficiencies and the error tabulated. Table V shows the results of this work. It may be noted that the maximum error involved is 8.2%. While the data of Figure VII appears to be unmanageable, it must be emphasized that the errors that caused this behavior were relatively small.

TABLE V

Approximate Formulae Applied to Tube Set No. 4.

η	L	V	V calc.	η for V calc.	Percent Error in η
31.4	3.07	500	494	31.4	0
40.0	"	900	840	39.3	-1.75
35.6	"	650	657	35.3	0
30.1	4.06	600	534	---	---
35.0	"	750	747	35.0	0
40.9	"	1050	1003	39.8	-2.7
35.8	5.09	850	897	37.2	3.9
40.3	"	1050	1205	43.6	8.2
45.6	"	1300	1354	46.1	1.1
36.0	6.20	1000	1033	37.0	2.78
40.0	"	1200	1234	40.75	1.9
45.0	"	1550	1483	44.5	-1.1
39.2	7.12	1200	1306	42.3	7.8
44.0	"	1400	1560	47.1	7.0
47.1	"	1550	1725	49.55	5.21

η , L and V - From data.

V (calc.) - Calculated voltage using approximate formulae.

η for V calc. - Obtained from data, entering with V(calc.) to nearest fifty volts.

Percent Error in η - based on η from the data.

A recommendation for further experimentation would be to select a wider range of tube lengths and diameters.

The primary data used in subsequent analysis appears in Figures V, VI, and X. Voltage was plotted from these curves as a function of tube length along constant efficiency lines. The constant efficiency lines were erected in all cases below the maximum points of the tubes used. Figures XI, XII, and XV show the results of this procedure. Both individual points and a fair curve are plotted. It should be noted that if the efficiency curves were plotted in their entirety, two values of voltage would appear for each tube at each efficiency except for one value at maximum efficiency. It can be seen that as the maximum efficiency of a given tube is reached, the slope, $d\eta/dV$, approaches zero. This appears in the voltage versus length curves as a departure from the straight line as tube length is reduced. Since two values of voltage can be obtained from each complete efficiency curve, it is possible to obtain two curves of voltage versus length. However, only the ascending portion is plotted and used. The descending portion of the efficiency curve is of little importance in this analysis. It should be noted also that as the efficiency line is increased, short tubes begin to disappear from the plot since they have reached a maximum value below the efficiency under consideration. This

shows clearly that if a certain efficiency is desired from a tube of given diameter, it may be necessary to use greater length both to obtain the desired efficiency and to operate the tube safely.

The upward swing of the voltage versus length curve at small length will always occur as the maxima of the efficiency curves are approached. The point where the departure from linearity occurs in the voltage versus length curves is offered tentatively as a limit for safe operation of the flashtube. No calculations are offered to define this point, although future work may indicate its feasibility.

There are no boundary conditions indicated on the voltage versus length plots at the high voltage end of the straight lines. There are indications in the 3.4 set efficiency curves that a limit does exist. However, this limit is not of immediate concern since equipment and measurement limitations will prevent rapid and thorough analysis of the high voltage, high efficiency region. It seems reasonable to assume a high voltage, efficiency limit since efficiency probably will not increase indefinitely with length. This high efficiency region will be of future interest undoubtedly, and this work indicates the path to be followed.

In deriving the equations presented in the results

only the linear portions of the voltage versus length curves are used. In fact, these linear portions are extrapolated to zero length with the full realization that this approximation approaches reality only as the efficiency level is reduced. If the expressions resulting from this thesis could be combined with another expression defining the lower limit of each efficiency level, the problem would have a much finer solution.

To pursue the analysis, straight line equations were written to express the voltage versus length curves in their linear region, which region is thought to be quite extensive through the higher lengths. The result was a series of equations which expressed the slopes of each line and the intercept on the ordinate at zero length. These equations originally were written for Figures XI, XII, and XV. These equations in themselves were not very illuminating. However, it was discovered that if the experimental number expressing the slope, m , of these lines were plotted versus efficiency, a significant relationship became evident. The series of experimental points appeared to approximate straight lines all of which passed through the origin. It was evident from this plot, Figure XVI, that the CL number was important since it was the only variable that appeared to influence the slope versus efficiency curve. The expression for m appeared to be of

the form;

$$m = k_3 f(\eta, C, L) \quad (8)$$

where k_3 was a proportionality constant. By trial and error this form resolved itself into,

$$m = \frac{65}{\sqrt{CL}} \eta \quad (9)$$

This form expresses the slopes of the voltage versus length curves very satisfactorily indeed. An inspection of Figures XI through XIV shows that the discrepancies between the calculated slopes and the experimental slopes are less than the errors involved in experimental measurement. It was at this point that the importance of $\sqrt{CL}$ was noticed. This explains its use on each of the graphs as a descriptive number instead of CL . It may be felt that the effect of tube diameter has not been adequately treated in this derivation. This same idea occurred to the authors during the derivation of the slope expression. It was decided to test for diameter effects by flashing tube sets 3.4 and 5.8 with different CL , capacitance - length numbers. Figures VIII, IX, XIII, and XIV show the results of this work. The conclusion was that the CL number and not the diameter clearly expressed the slope concept. An examination of Figures XII and XIII, where the CL numbers are essentially the same but diameters are different, reveals the fact that the slopes are also essentially the same.

The analysis to this point had been so direct and illuminating that the authors held high hopes for a simple and revealing exposé of the complete expression. Consequently, methods similar to those used in expressing the slope were used in analyzing the intercept numbers. It became increasingly evident that a simple expression for the intercept, b , did not exist. Figure XVII shows experimental points and faired curves for intercept versus efficiency. The points plotted are only representative ones and are by no means all of the obtainable points. An examination of Figure XVII shows a rather wide dispersion of points. It should be remembered that these points are not obtainable through experimentation. They represent the voltage that exists at zero length for the voltage versus length curves. It is inevitable that the plotted points be widely dispersed since many approximations and assumptions are necessary in order to obtain them. An attempt was made to express the fair curves in the following terms;

$$b = k \eta^x \quad (10)$$

where x is an unknown exponent. The curves could be expressed by this relation only for very high values of x . In fact, x seemed to approximate $\frac{65}{\sqrt{CL}}$ for both the 3.4 and 5.5 sets. This large exponent yielded a number so great for η^x that the practical use of the expression was

prohibited. During this analysis, the effect of $\sqrt{CL}$ was investigated. Points for each tube diameter regardless of $\sqrt{CL}$ tended to plot on the same curve. The unreliability of the data consequently made it necessary to assume that $\sqrt{CL}$ had no practical effect. These reasons indicated that an overall approximation would be the only means by which an analytical expression for b could be obtained. The only clearly discernible parameter for the plotted points was tube diameter. Consequently, tube diameter formed the basis for the approximation. Two straight lines were assumed for the curve of each tube set. The four resulting straight lines were subsequently adjusted to bear expressible relationships among themselves and to approximate the data with reasonable accuracy. The derivation of the expressions for b is illustrated in Appendix B, and the expressions are also stated in Figure XVII. The greatest criticism that can be made of these expressions is that they fail to express the intercept adequately at very high efficiencies. The intercept tends to become asymptotic to a constant efficiency line. This constant efficiency asymptote is not the same for tubes of different diameters.

If this expression for b is examined as a part of the total equation its errors are found not to be prohibitively large. Both experimental and calculated values are indicated in Figures XI through XV. The calculated values are expressed by equations (4), (5), and (6), and

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it may be seen that the difference between the analytical expressions and the experimental curve rarely exceeds 3%.

The above discussion completes the work involved in obtaining an expression for tube behavior within the restrictions of this thesis. As indicated in the section devoted to results there were observed effects which might be termed "incidental" but which may hold greater significance for future experimenters than the analytic expression. The subject of crazing is important. Any analysis is extremely difficult since crazing can first occur at only one point for a given tube. After that point has been reached, it is possible to evaluate the degree of crazing only in a qualitative manner.

It was found that crazing generally occurred beyond the peak of the efficiency curve regardless of the voltage or capacitance applied. At low values of capacitance the efficiency curves are quite flat. Consequently, it is difficult to define the maximum point exactly. The ideas concerning crazing should therefore be tested in the low capacitance region before the ideas are accepted completely. Since an investigation of crazing was an incidental part of this thesis, all tubes were crazed before this experiment could be conducted. It is known that the number of flashes and the flash rate during a tube's life is definitely limited. The energy level at which the tube is flashed

enters into tube life also. The quantity which has been of greatest interest has been the efficiency and energy level at which crazing first appears. Consequently, the question of tube life does not enter the problem directly. The flashtubes used in the experimental work were not tested for total life. They have all been crazed to a certain extent, and all tubes have been flashed at least two-hundred times but not more than four-hundred times. There appears to be no correlation between number of flashes and degree of crazing in this experiment.

Contamination of flashtube gas is a subject which is difficult to study in any but a qualitative manner. The observed effects in the experimental work are stated in Results. There is little more that can be added to what has already been stated.

Many experimenters believe that the current density in the flashtube during the discharge holds the solution to flashtube operation. Nothing in this thesis tends to disprove this idea. Casual observations were made to discover whether or not the discharge filled the entire flashtube. No departure from a full flash was observed, although it was noticed that the discharge extended only between the tips of the electrodes. The flash boundary was clear cut, and it existed as a plane perpendicular to the axis of the flashtube at the electrode tip.

There are many opportunities for further research in flashtube operation, and the authors believe that much valuable information can be gained from it. Ideas are presented in Recommendations which represent the various courses that the authors think could give further information. If time had permitted, many of these ideas would have been exploited.

CONCLUSIONS

1. The derived expressions define flashtube behavior with a maximum error of approximately five percent.

These expressions are:

$$V = \frac{65L}{\sqrt{CL}} \eta + 135 D^2 \eta \quad (4)$$

$$V = \frac{65L}{\sqrt{CL}} \eta + \frac{13.3}{D^{1/2}} \left[\eta - \frac{8.3}{D^{2/3}} \right] \quad (5)$$

$$\eta = \frac{8.3}{D^{2/3} [1 - 10.12 D^{1/2}]} \quad (6)$$

2. The expression for slope of the voltage versus length curves defines this quantity accurately; the expression for the intercept of the voltage versus length curves is an approximation to the actual intercept behavior.

3. No simple proportionality concept exists between voltage and length and input energy and tube volume.

The product LC, length in inches and capacitance in microfarads, is important in defining flashtube operation.

4. If L is held constant for a series of tubes of constant diameter, the maximum attainable efficiency increases with increase in length, but the voltage for maximum efficiency must also increase with length.
5. If diameter is increased, higher efficiencies are attainable for a given tube length.
6. The boundary for safe operation of a flashtube can be established as that point at which the voltage versus length curve departs from a straight line.
7. Crazing of flashtubes generally occurs beyond maximum efficiency regardless of voltage and capacitance applied.
8. Crazing does not affect tube operation apparently until its severity causes a filtering action of light output. Contamination through crazing was not observed.
9. Contamination of tube gas apparently affects only the starting qualities of the tube if the contamination is only partial.

RECOMMENDATIONS

1. The solution to the problem of flashtube operation as presented in this thesis applies only to what is termed a practical operating range. A more general solution might be possible if the equation for the complete efficiency curve could be written. The authors believe that this could be done within the limits of this thesis. More information is needed in the region beyond maximum efficiency. Tubes should be constructed of quartz to minimize damage in this region. The proposition concerning efficiency curve symmetry could also be fully explored.
2. A greater range of tube dimensions should be used with larger gradations between units in order to prevent obliteration of significant factors through small errors.
3. The ratio of length to diameter should possess some significance since it is a number which defines geometric similitude. Future investigation might prove this number to be a valuable parameter.
4. An investigation should be made of the possibility of defining the point at which the voltage versus length curve departs from a straight line. This probably will entail work outlined in the first recommendation.
5. Data should be accumulated systematically to verify the ideas presented in regard to crazing.
6. A more detailed study should be made of the intercept, b , in an attempt to arrive at its exact expression.

7. Gas pressure may very well be a key variable. Studies should be made among flashtubes with different gas pressures.
8. While it seems doubtful that the type of gas would enter the problem as a simple variable, experimental results can be useful only if they are generally applicable. This study probably would serve as the important link between experimental results and theoretical concepts.
9. A study of flashtube configurations and reflectors is somewhat beyond the theme of this work. A thorough investigation, however, should prove of inestimable value.
10. Studies should be made of the volt-ampere characteristics of flashtubes of different designs.
11. An investigation of spectral variations in flashtubes could logically be conducted in conjunction with studies of types of gases and gas pressures.

A P P E N D I X

APPENDIX A

1. Light Measurement

The light integrating meter used has two filter or dispersing discs and a polaroid attenuator before the photocell on the input side. With an attenuator setting of 1, and both discs in place, the meter is factory calibrated to indicate lumen seconds per square foot. To obtain consistent results, several modifications in meter operation were found necessary.

To obtain the sensitivity required one of the filter discs was removed to allow sufficient light to enter the meter to give a meter reading high enough on the scale for satisfactory accuracy. This did not detract from the linearity of the meter to any noticeable extent as indicated in the table later in this section.

Since sufficient evidence was found in preliminary runs to throw suspicion on the linearity of the meter at different attenuator settings, it was decided to adjust distance rather than attenuator setting to give the ranges desired. Therefore a wooden bench was constructed with a fixed meter platform and a moveable carriage for the tube mount. On this bench scale factors were scribed as indicated below.

A standard was established, using the meter with both discs and an attenuator setting of 1, at a distance

of 2 feet. (An attenuator setting of 1 was maintained throughout the research.) The tube selected for the standard was an FT-214 marked "Standard No. 5". At this setting, light output was equal to the product of the meter reading and distance squared, or meter reading times four.

With one disc removed, distance was adjusted until the readings obtained with both discs in were duplicated at corresponding values of capacitance and voltage. At this distance a line was scribed on the bench, and a factor of 4 indicated. Table VI shows the results of one such run, as well as percent deviation in meter indication.

TABLE VI

Bench Calibration

Voltage	Meter Indication		% Deviation
	Two Discs*	One Disc**	
1000	27.0	27.0	0
1200	44.3	47.0	+4
1400	74.0	73.25	-1
1600	105.0	104.0	-1
1800	141.0	133.0	-2

C = 84.8 microfarads

* Distance = 2 feet

** Distance = 4 feet 4-3/8 inches

The percent deviation shown is within the combined possible error of meter and repetitive ability of the tube, each being quoted as within 5%.

In a similar manner distances were established and lines scribed for factors of 1, 2 and 8. This was carefully done with a result that the data obtained shows no radical bumps or jumps at points where changes in scale were effected.

It should here be noted, as a word of warning resulting from sad experience, that pains must be taken to keep the filter discs clean at all times, washing them either with warm water or alcohol. Much data, painstakingly acquired, had to be discarded by the authors before a policy was established of washing the discs prior to each day's work.

It also should again be stated that although the meter was factory calibrated to read directly in lumen seconds per square foot, there is no proof that it still does so. Therefore values of efficiency are given relative to a standard as indicated rather than as absolute quantities.

2. Power Source

The power source used is an experimental console employed extensively in the Stroboscopic Laboratory. It is capable of supplying 4,000 volts across a variable

capacitance of 0.37 to 129 microfarads, and has external taps through which more capacitance may be introduced.

As shown in Figure IV, capacitance is selected by setting each of the three dials to values obtained from a chart. Each dial has three capacitor settings as well as two "off" positions. The equipment itself has an inherent capacitance of 0.37 microfarads. By means of a capacitance bridge, readings were taken at each dial position, and deviation from tabulated values was found to be much less than 1%. Therefore tabulated values were used. Rechecks were made at regular intervals to ensure there was no change in capacitance values.

Since the voltmeter mounted on the cabinet is a 2% meter with a range of 3,000 volts, and is difficult to read accurately at relatively low voltages, Weston multirange voltmeter designated 463.3213 was rigged with external multipliers ($\pm 1\%$ wire wound resistors) to give ranges of 0-1500 and 0-3,000 volts. The latter is a 1/2 % meter. Both it and the cabinet meter were checked against electrostatic voltmeter M12096, which had recently been repaired and calibrated, and errors were found to be well within experimental limits. In taking data, since the external center tap of the source was found to have been accurately placed, measurements were taken across half the source allowing the 0-1500 volt

range to be used exclusively.

3. Tube Manufacture

Tubes used in this research were shaped by the glass blowers in lengths as directed, normal tolerance being 0.125 inches. All tubes of one diameter were made from a common length of pyrex tubing except when extra tubes were ordered. In the latter case, care was taken to match diameters, but wall thickness could not be maintained precisely the same.

The tubes received were then processed by the authors following the steps listed in sequence. This processing was conducted using the equipment located in the Stroboscopic Laboratory. The steps are as follows:

- a. Mount the tubes on the pumping system and evacuate them as completely as possible.
- b. Heat with a gas flame until the characteristic sodium glow appears, in order to drive out the impurities in the glass.
- c. Continue evacuating the system.
- d. Isolate the tubes from the pump and introduce xenon into the tubes at a pressure of 1-1/2 cm. hg.
- e. Apply a voltage, to each electrode in turn, sufficiently high to make the electrode attain a red heat in order to drive off impurities in the

metal.

f. "Scrobe" the tubes to finish driving off impurities.

g. Again apply a vacuum to the system by means of the pump, and evacuate the tubes as completely as possible.

h. Isolate the tubes from the pump and introduce xenon into the tubes at a pressure of 15 cm.hg.

i. Seal off the tubes and remove from the system.

j. Wind the starting bands on the tubes. (The starting band consists of turns of light wire wound around the tube along the length between electrodes. In this case, turn spacing was from $3/8$ to $1/2$ inch for all the tubes used).

4. Preliminary Methods and Analysis

From the data obtained, efficiency was calculated and curves of efficiency vs. voltage plotted. With this information, curves of efficiency vs. length were plotted for voltage gradients from 200 volts/inch to 350 volts/inch. Figure XVIII shows a set of these curves for tubes of 0.217 inch diameter. It was found that these curves formed straight lines in the so-called useable portion, and an increasing slope with increasing voltage gradient. However there appeared boundary conditions which seriously limited the possibility of writing an analytic expres-

sion. As voltage gradient or energy level increased, the efficiency curves for the smaller tubes reached a maximum and then fell off. This occurred also for the larger tubes when energy level or voltage gradient was excessive.

In conjunction with the above, another family of curves was plotted to further the analysis and to verify data with the idea that the length to diameter ratio might be a more important value than either of these alone. Furthermore, it was felt that information could be obtained between sets having different diameters. Consequently, plots were made of length/diameter vs. efficiency--see Figure XIX for sample plot--maintaining voltage gradient constant, and using data from the faired curves of efficiency vs. length. On these plots the points for tubes of a given length were connected by a fair curve. Here a quantitative analysis appeared to be difficult if not impossible. However, this work was not in vain, providing two measures of assistance. In conjunction with the previous plots, good data was corroborated, and faulty data (erratic behavior of tubes) was exposed. Furthermore, they served to increase qualitative understanding of fundamental behavior.

At this point curves of voltage vs. length with efficiency held constant were plotted, and the analysis,

as described in the main body of the thesis, ensued.

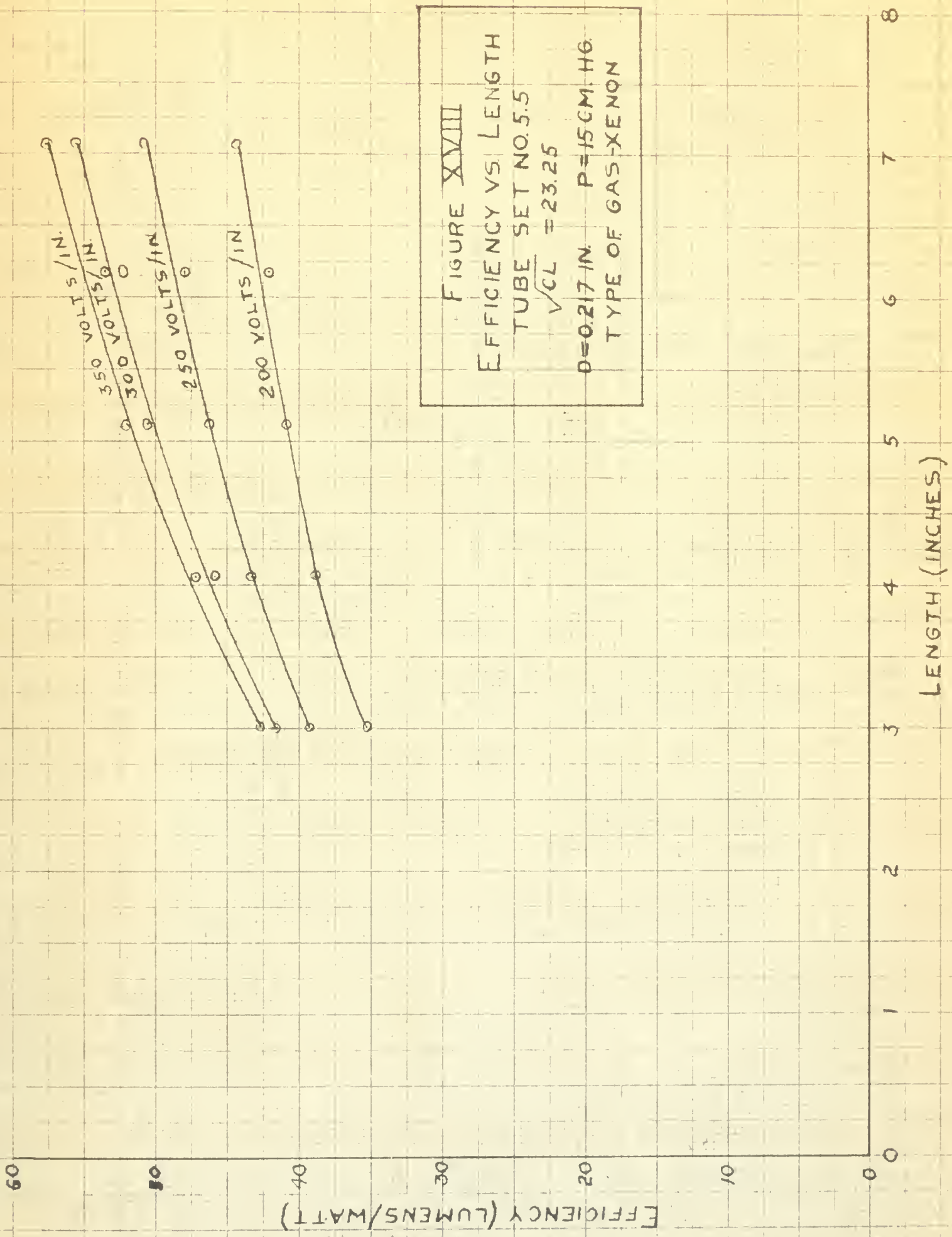


FIGURE XVIII
 EFFICIENCY VS. LENGTH
 TUBE SET NO. 5.5
 $\sqrt{CL} = 23.25$
 $D = 0.217$ IN. $P = 15$ CM. HG.
 TYPE OF GAS-XENON

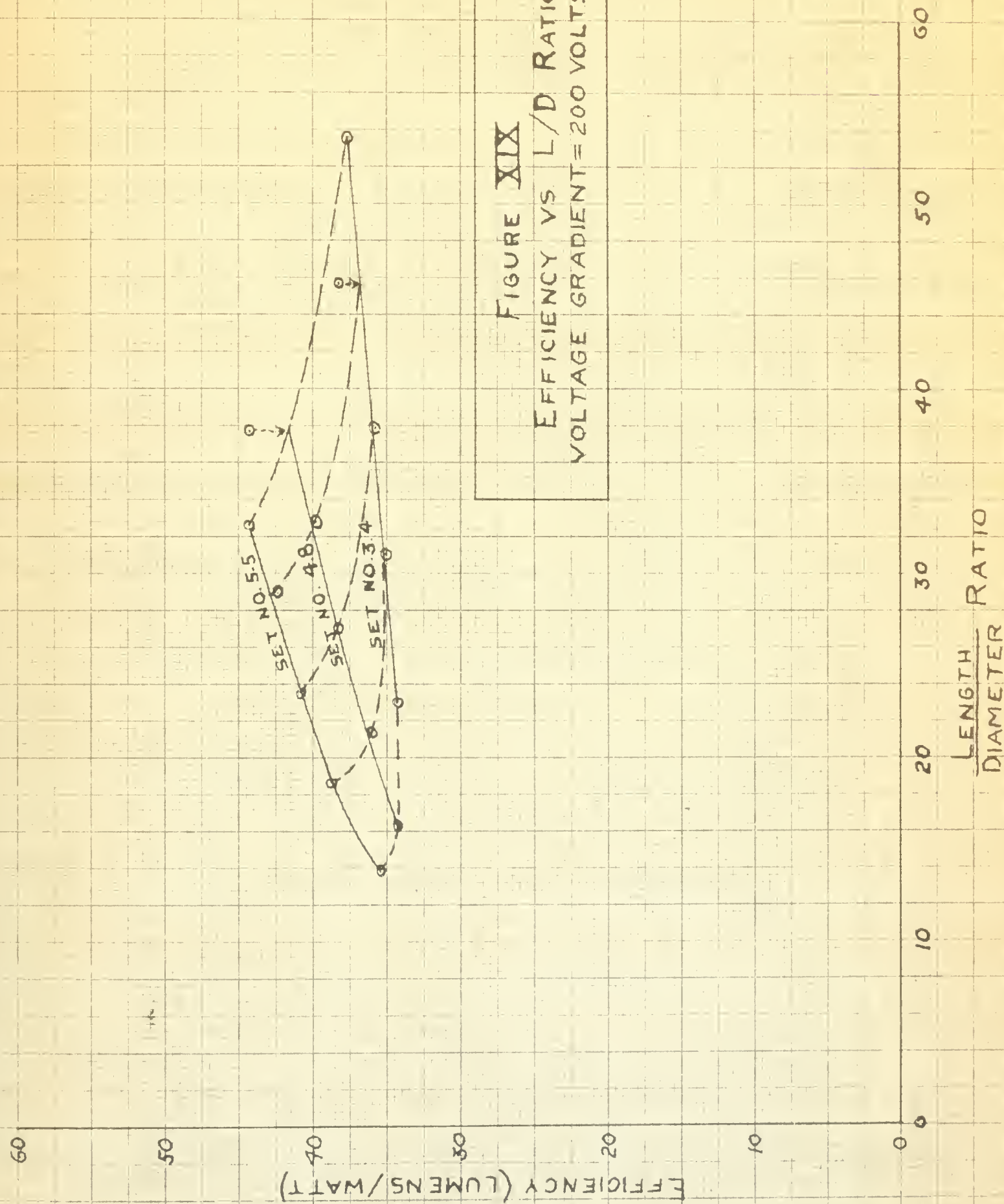


FIGURE XIX

EFFICIENCY VS. L/D RATIO
VOLTAGE GRADIENT=200 VOLTS/IN.

APPENDIX B

ORIGINAL DATA AND CALCULATIONS

All original data has been filed with Professor H. P. Edgerton in the Stroboscopic Laboratory.

Calculations involved in this research are few and simple.

(1) Method of choosing values of capacitance:-

$$V = K_1 L$$

$$\frac{CV^2}{2} = K_2 \times \text{VOLUME}$$

$$\frac{CV^2}{2} = K_2 \frac{\pi D^2}{4} L$$

$$\frac{C(K_1 L)^2}{2} = K_2 \frac{\pi D^2}{4} L$$

$$C = \frac{K_2}{K_1} \frac{\pi D^2}{2} \frac{1}{L} \quad K_1, K_2 \text{ ARE CONSTANTS}$$

∴ for a given set of tubes of constant diameter

$$C \propto \frac{1}{L}$$

∴ for a given set of tubes of constant length

$$C \propto D^2$$

(2) Method of determining slope "m":-

It was first assumed that

$$m = K_3 f(\eta, C, L)$$

From the plot of η vs. efficiency, Pl. XVI,
it was determined that

$$m = K_3 \frac{\eta}{\sqrt{CL}}$$

$$\therefore K_3 = \frac{m \sqrt{CL}}{\eta} = 65$$

(3) Method of determining intercept "b":-

In a manner similar to that in part (2), above,
straight line approximations were made for the
intercept, assuming that

$$b = K_4 f(\eta, D)$$

It was found necessary to use two straight lines
for each diameter to minimize the attendant
error. For low values of efficiency

$$b = 135 D^2 \eta$$

For larger values of efficiency

$$b = \frac{133}{D^{1/2}} \left[\eta - \frac{83}{D^{2/3}} \right]$$

To find the break or transition point it was
only necessary to solve for efficiency at the
intersection of the two lines

$$135 D^2 \eta = \frac{133}{D^{1/2}} \left[\eta - \frac{83}{D^{2/3}} \right]$$

$$\eta \left[\frac{133}{D^{1/2}} - 135 D^2 \right] = \frac{133 \times 83}{D^{1/2} D^{2/3}}$$

$$\eta \left[1 - 10.12 D^{5/2} \right] = \frac{83}{D^{5/3}}$$

$$\eta = \frac{83}{D^{5/3} [1 - 10.12 D^{5/2}]}$$

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